NASA
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integration

Human Systems Integration Handbook

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FOREWORD

Systems Integration (SI) at NASA is a key engineering function for every project. Bringing this collection of complex subsystems or disparate parts together to form a single entity that functions and performs to mission needs is paramount to the success and value of that mission. Accounting for the human interface as another piece of SI is necessary to achieve every aspect of mission success, and just as critical as the hardware we assemble. From an engineering perspective, Human Systems Integration (HSI) means not only making certain that the systems we design are friendly to the end user, safe, and resilient, but also ensuring that all phases of life-cycle development that involve humans are integrated in a cohesive manner that results in the highest probability for mission success. Early in my space industry career, manufacturing engineers were not consulted until the integration phase of the development flow, when it was often too late to gain efficiencies. The need to bring those engineers into the flight hardware design phase at inception was obvious and resulted in a superior flight design that was more efficient from a cost and integration schedule perspective. I see a similar corollary with HSI. This unique expertise needs to become a part of systems integration during development, implementation, and execution of missions if we are to achieve success with the challenges ahead.

Mr. Joe Pellicciotti
NASA Deputy Chief Engineer

The proper integration of the human into the development, deployment, and operation of our systems is recognized as a significant factor in the safety and success of our missions. For instance, NASA defines a human-rated system—its designation for systems used to conduct crewed spaceflight missions—as one that accommodates human needs, effectively utilizes human capabilities, controls hazards with sufficient certainty to be considered safe for human operations, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations. This definition covers many of the HSI domains defined in this handbook. A structured understanding of these domains, underlying objectives, and relevant standards and processes to meet those objectives is important for all our missions—human exploration, science, and aeronautics. This handbook brings together insights and practices contributed by HSI practitioners from across the Agency. I hope it will be a great resource to the NASA community and positively affect HSI practices across our missions. I thank everybody who contributed.

Dr. Frank Groen
NASA Deputy Chief of Office of Safety and Mission Assurance

Throughout the history of transportation, mismatches between human and machine have resulted in decreased human performance at a minimum and, sadly, in some cases, fatal mishaps. The Office of the Chief Health and Medical Officer, through its role as NASA's Health and Medical Technical Authority, is concerned with optimizing human performance and ensuring any humans involved have a healthy workplace. As NASA pushes the boundaries of space and atmospheric exploration, we challenge the human limitations and place humans in extreme environments. Human Systems Integration is essential to ensuring the capabilities and limitations of the human are considered early in system and mission design. Humans are involved in all projects and programs, from spaceships to aircraft to satellites and robotic rovers. Humans are involved in every aspect, from human interface in manufacturing, maintaining, or guiding a satellite; controlling robots on another planet on a different day/night cycle; building and operating new electric airplanes; operating a lunar base of operations; or performing human research in Antarctica. Humans are the common denominator. Integrating the hardware and software with the human in mind is critical to the overall mission success and protects the health and well-being of our greatest NASA resource—our people. This guide is an essential tool for anyone involved in, planning for, or ensuring Human Systems Integration.

Dr. Vince Michaud
NASA Deputy Chief Health and Medical Officer

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Preface: Background on NASA Human Systems Integration

The field of Human Systems Integration (HSI) evolved from the disciplines of industrial engineering and experimental psychology and lessons learned during World War II, when discipline practitioners witnessed poor system designs that were often unsafe and difficult to operate. Following World War II, the U.S. armed services recognized the need for greater attention to human-centered design, and the field of HSI began to emerge. The focus of the new methodology was to address a rapid increase in mishaps, staffing demands, and personnel and training costs, and also to reduce total life-cycle systems costs. Its practices were rapidly adopted by the military to control costs and improve mission outcomes. Since the early 1960s, NASA has had its own rich heritage of employing human factors for the protection of its spaceflight crews, with a focus on human health and performance in spacecraft and mission design.

Marshall Space Flight Center (MSFC) wrote the initial standards that formed the foundation of what we, as an Agency, now call HSI. In 1965, *MSFC-STD-391, Human Factors Engineering Program*, was created to establish minimum human factors requirements to promote the maximum effectiveness and reliability of humans as a system component. This standard described a “system” as an optimal combination of mission and support personnel, equipment, facilities, and procedures. Then in 1966, MSFC published *MSFC-STD-267A, Human Engineering Design Criteria*, presenting human engineering design principles and practices to be used by engineers in designing equipment for the satisfactory performance of operator, maintenance, and control personnel; reduced skill requirements and training time; increased reliability of personnel-equipment combinations; and a basis for design standardization of large Earth-launch booster systems. Following the Apollo Applications Program, this standard was revised for spaceflight design, based on Skylab experience and neutral buoyancy experimentation. It was assigned the number MSFC-STD-512 and titled Man-System Requirements for Weightless Environments. The new standard became the basis for NASA-STD-3000, which was created in the 1980s, using Agency-wide subject-matter expertise to inform the development of the space station program that eventually became the International Space Station. NASA-STD-3000 similarly became the basis for NASA-STD-3001, which provides an update to the content for Beyond Earth Orbit exploration.

These standards incrementally advanced human-rated missions and simulators. In the 1970s and ’80s, NASA improved aviation safety and matured concepts in crew resource management. In the late ’90s, the Department of Defense (DoD) was facing rapid and ubiquitous escalation in life-cycle systems costs. It became clear that better design practices for inclusion of the human elements required to develop, deploy, and operate a system needed to become standard in life-cycle systems engineering (SE) and program and project management. Army General Max Thurman asserted, “We must quit manning the equipment and start equipping the man.” [ref. 1] Synergistic interaction between a system and its human elements is key to attaining expected total system performance outcomes and minimizing total ownership costs. Therefore, to realize the full and intended potential that complex systems offer, the DoD was the first U.S. government agency to identify the need for better design processes for early and thorough consideration of the human element in systems design, when it mandated in 2003 that a “total system approach” must apply HSI to all developments.

In 2008, *NPR 8705.2B, Human-Rating Requirements for Space Systems*, was updated to include additional emphasis on the process of achieving human rating, emphasis on application dependency, and emphasis with respect to Systems Engineering context and analysis. The human-rating requirements define and implement processes, procedures, and requirements necessary to produce human-rated space systems and define a human-rating certification path for program managers (PMs) and their teams to follow in conjunction with traditional program management milestones. In 2010, NASA published the *Human Integration Design Handbook for Human Space Flight*, further enhancing NASA's focus on human-centered design (HCD). HCD is a performance-based approach that focuses on making a design usable by humans throughout a system's life cycle [ref. 2]. It is characterized by early and frequent user involvement, performance assessment, and an iterative design-test-redesign process. HCD is an outcome achieved through proper implementation of HSI. Also during this period, NASA HSI pioneers began to work toward a NASA-specific HSI implementation, initiating efforts to update NASA's SE documentation to be more inclusive of HSI and the human element. As a result, in 2013, *NPR 7123.1B, NASA Systems Engineering Processes and Requirements*, included the first formal definition of HSI in NASA documentation.

In 2014, NASA released *NASA/TP-2014-218556, Human Integration Design Processes (HIDP)*, which captures NASA human engineering and HSI lessons learned to supplement standards and requirements alone—i.e., complex, iterative processes such as determining the appropriate net habitable volume of a spacecraft for a given crew size, mission scope, and mission duration.

In 2015, *NASA-STD-3001, NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health*, was updated with a new requirement for HCD. Inclusion of this requirement for all human spaceflight programs was a significant step forward in capturing and documenting NASA's approach to HSI. At this time, the requirement applies to human spaceflight programs, but not to other NASA programs, such as aviation and uncrewed space exploration. Nonetheless, an HCD approach to system acquisition and development is a critical human factors concept contributing to HSI.

Additionally, in 2015, the *NASA HSI Practitioner's Guide (HSIPG)* was published [ref. 3]. This initial HSI guide provided much-needed guidance on HSI team responsibilities, activities, and products, along with guidance on writing an HSI Plan (HSIP). The HSIPG set the bar as a guiding document, primarily for human spaceflight missions. This handbook and associated policy changes demonstrate a commitment to advancing HSI efforts across all mission types within the Agency and its contractor activities. The handbook also captures many of the advancements and lessons obtained through the application of HSI since 2015.

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1.0 Introduction

1.1 Purpose and Applicability

This handbook is intended to provide general guidance and information on Human Systems Integration (HSI) and its applicability to NASA programs and projects and the wider NASA community. Its primary purposes are to increase awareness and consistency across the Agency, enable the advancement of the practice and implementation of HSI principles and processes, and provide invaluable information and guidance to HSI practitioners in the performance of their duties. Implementation of an HSI approach will enhance NASA's core engineering capabilities while improving safety, mission success, and affordability.

The specific aims of this handbook are to define HSI; illustrate its value in programmatic decisions; demonstrate how it fits into the NASA project life-cycle process; describe how it applies across all NASA missions; describe how it integrates knowledge and methods from multiple disciplines; describe the checks and balances provided by the three Technical Authorities; provide guidance on HSI processes, procedures, and products; and provide helpful information on HSI resources within the NASA community.

This handbook should be used as a companion for implementing *NASA Procedural Requirements (NPR) 7123.1, Systems Engineering Processes and Requirements*, the *NASA Systems Engineering Handbook*, NASA directives, and any Center-specific handbooks and directives developed for implementing programs and projects.

As of 2021, both NPR 7123.1 and *NPR 7120.5, NASA Space Flight Program and Project Management Requirements*, require HSI to be implemented within NASA technical efforts. These efforts are to be documented in a Human Systems Integration Plan (HSIP), and the intent is to update the NASA 7100 series of procedural requirements as they are renewed. The purpose of the HSIP is to document and plan the scope of HSI, whether on a reduced scale for a small project or as a comprehensive implementation for a major program; identify the steps and metrics used throughout the project's life cycle; identify the HSI domains engaged in the effort; and document HSI methodologies and approaches to ensure effective implementation. HSIPs are required for the following Agency efforts, as defined by 7120.5: projects, single-project programs, and tightly coupled programs. This handbook will provide guidance on planning and implementing HSI activities for these efforts and provide a comprehensive, yet tailorable, HSIP template.

HSI processes should be tailored to the size, scope, and goals of individual programs and projects. The instructions and processes identified here are best used as a starting point for implementing human-centered system concepts and designs across programs and projects of varying types, including crewed and uncrewed, human spaceflight, aviation, robotics, and environmental science missions. For programs and projects that adhere to *NPR 8705.2C, Human-Rating Requirements for Space Systems*, the requirement is for the Program Manager at System Requirements Review (SRR) to "establish a Human-Systems Integration (HSI) team comprising representation from the systems user community (e.g., astronauts, mission operations personnel, training personnel, ground processing personnel, human factors and human-systems integration SMEs), with defined authority, responsibility, and accountability in support of the program's HSI Plan for the crewed space system." It should be noted that this handbook is not fully aligned with the required NPR 8705.2C establishment of an HSI team in composition or timeline; however, it is expected that NPR 8705.2C will undergo revision later in 2021 to align with the guidance in this document.

1.2 Motivation for this Handbook

Systems have become increasingly complex, often due to the enormous capabilities and advances of micro-circuitry and digital firmware/software. Now the intention to mimic human behavior and decision-making in automated, semi-autonomous, and autonomous systems adds further complexity, including novel opportunities for system errors. Early and careful consideration of the human performance characteristics and behavior when interacting with such complexity has become essential to planning and designing for total system performance and outcomes. Hardware and software systems enable humans to perform advanced mission tasks and objectives in extreme and potentially lethal environments. Likewise, humans enable hardware and software to perform advanced mission tasks in the same environments. Humans provide resilience to systems in the event of unexpected off-nominal events. Systems can be designed to require highly specialized and trained personnel or accommodate a broad population of human capabilities. The range of intended roles for humans requires varied design strategies. All of the above illuminates the need for HSI application across all mission and project types within NASA. The goal of this document is to ensure HSI is carefully considered and planned from the outset of any NASA program or project. To aid the reader, this handbook provides references throughout to a set of case studies (see Appendix D) that showcase real-life HSI examples of the topics presented in particular sections.

Background on NASA's HSI thinking, guidance, processes, and implementation is provided in the Preface, describing efforts that span several decades. However, NASA subject matter experts (SMEs) continue to discuss HSI best practices and lessons learned as applicable to NASA missions and projects. In recent years, NASA has begun to realize HSI principles were not being applied across all missions and projects. Recent and impending policy changes demonstrate a commitment to advancing HSI efforts across all mission types within the Agency and in contractor and partner activities. This NASA HSI Handbook captures many of the advancements and lessons obtained through the application of HSI since 2015, when the HSI Practitioner's Guide was published as NASA/SP-2015-3709, and this document supersedes that publication.

2.0 Human Systems Integration Fundamentals

2.1 What are HSI, HSI Practitioner, and HSI Lead?

2.1.1 Definition of HSI

Within the engineering community, a *system* is largely thought of as the integration or assemblance of hardware and software that together perform a function. HSI considers a system to be the integration of hardware, software, humans, data, procedures, and processes, considering the environment in which it is situated. The *human* in HSI refers to all personnel involved with a given system, including owners, users, customers, designers, operators, maintainers, assemblers, support personnel, logistics suppliers, training personnel, test personnel, and others.

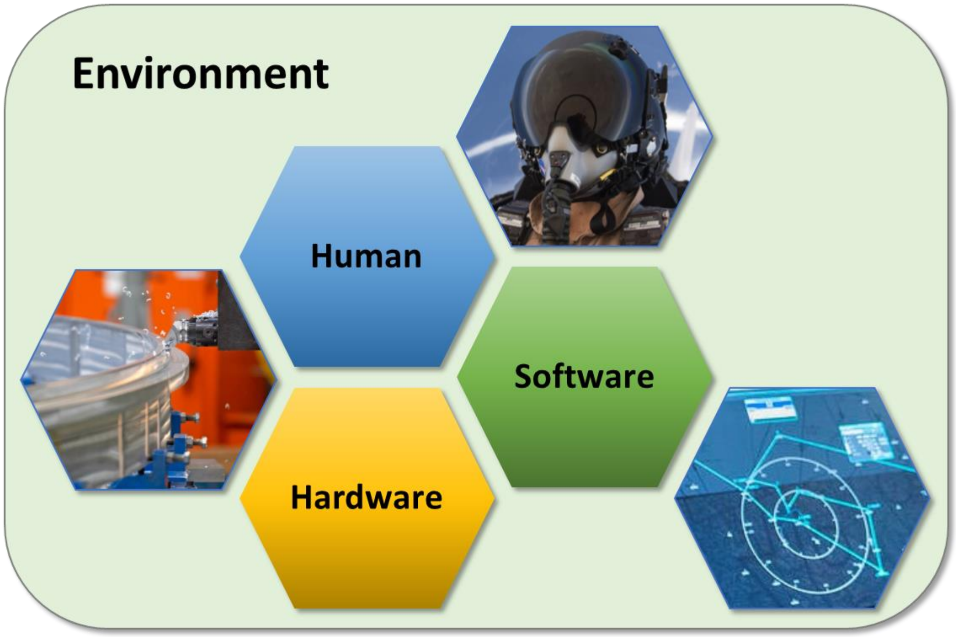

Figure 1-1. HSI System: Integrated Hardware, Software, and Human Elements within an Environment

NASA systems are designed to fulfill mission goals and scientific objectives by addressing various stakeholder needs and constraints. In 2020, the newly formed NASA HSI Community of Practice, noticing inconsistencies in NASA documentation with respect to the definition of HSI, reassessed the Agency's definition and domains for the purpose of NASA Programs and Projects. These are further described in Section 2.2.

What is Human Systems Integration?

As defined by the NASA HSI Community of Practice, HSI is a required interdisciplinary integration of the human as an element of a system to ensure that the human and software/hardware components cooperate, coordinate, and communicate effectively to successfully perform a specific function or mission.

It is important to note that the definition of HSI varies across government agencies, industry, and academia and not just within NASA. HSI is, however, built on scientific research into human needs, capabilities, and limitations, as well as knowledge of how humans work in socio-technical systems to create successful missions and respond to novel and unexpected events. While NASA has defined HSI as part of the SE process, the DoD has noted that HSI has also been defined as a philosophy, an approach to SE (or even a SE discipline), a set of processes, and a goal [ref. 4].

- A philosophy: By definition, HSI is a human-centered mindset; a way of thinking instilled in those who design, build, and manage a system throughout its life cycle. By definition, a system consists of hardware; software; and the humans who operate, maintain, and support that system within a given environment.
- An approach to SE: Those responsible for designing, testing, fielding, and managing systems must ensure human performance characteristics provide the foundation for SE.
- A set of processes: The tenets of HSI are realized through the tools, techniques, approaches, methods, and standards that enhance the SE process.
- A goal: The goal of HSI is to optimize total system performance through effective human integration with system hardware and software while minimizing program costs and risks.

NASA is, and has been, working jointly with DoD to define, learn, evolve, and leverage lessons learned with respect to HSI, and regularly engages in forums to exchange thoughts and perspectives. NASA is a partner member on the DoD Joint HSI Working Group, has a representative on the Operating Board of the DoD HFE Technical Advisory Group, and participated in the development and review of SAE-6906 (adopted by DoD as a standard practice for invoking HSI in contracts for system acquisition). Members of the broader HSI community also engage routinely to exchange information.

SAE-6906 defines HSI as a comprehensive management and technical approach applied to systems development and integration as part of a wider systems engineering process to ensure human performance is optimized to increase total system performance and minimize ownership costs.

Similarly, DoD defines HSI as a comprehensive, interdisciplinary management and technical approach applied to system development and integration as part of a wider systems engineering process to ensure that human performance is optimized to increase total system performance and minimize total system ownership costs [ref. 5]. HSI enables the SE process and program management effort that provides integrated and comprehensive analysis, design, and assessment of requirements, concepts, and resources for seven domains: human factors engineering (HFE), manpower, personnel, training, safety and occupational health (SOH), force protection and survivability, and habitability. These HSI domains are interrelated and interdependent and must be among the primary drivers of effective, efficient, affordable, and safe system designs. HSI integrates and facilitates trade-offs among these domains and other systems engineering and design domains but does not replace individual domain activities, responsibilities, or reporting channels.

It is imperative to take a system of systems approach that begins with concept development and continues throughout the project life cycle. While the NASA definition of HSI and the DoD HSI definition read differently, the underlying philosophy and foundational principles are the same.

The INCOSE SE Handbook [ref. 6] states that the primary objective of HSI is to ensure that human capabilities and limitations are treated as critical system elements, regardless of whether humans in the system operate as individuals, crews, teams, units, or organizations. The *human* in HSI refers to all personnel involved with a given system, including owners, users, customers, designers, operators, maintainers, assemblers, support personnel, logistics suppliers, training personnel, test personnel, and others. A system is more than hardware and software; it is composed of hardware, software, data, procedures, and humans. Many engineers consider data and procedures part of a system's hardware and software components. However, it is important to consider all five components individually, as well as the integration and interfaces among them. HSI domains collectively define (a) how human performance characteristics affect system development in terms of its overall design, effectiveness, operation, support, and the associated cost and affordability of these components, and (b) how the system hardware, software, and environment affect human performance. Total system performance is a measurable outcome of the effectiveness of the integrated interaction of hardware, software, and human elements.

HSI Brings Unique Value to NASA Programs and Projects

- Maximizes total system performance, safety, and operations by considering the human in the system's design, engineering, and operational environments.
- Identifies human performance characteristics within system design.
- Identifies and mitigates, where possible, risks to programs and projects of record and performs trades across cost, schedule, and technical performance.
- Reduces life-cycle cost (LCC) through early identification and mitigation of risks, avoiding late re-works and increased operating costs.

If HSI is not properly applied in the earliest stages of a project and appropriately funded within NASA, the impacts can include:

- Increased risk to human life and hardware/software.
- Increased risk of rework.
- Increased LCC.
- Increased risk to schedules.
- Increased risk to mission success.

2.1.2 Definition of an HSI Practitioner and HSI Lead

There has been considerable discussion over the years as to the definition of an HSI practitioner within the NASA community, DoD, and industry since HSI is not a single discipline taught in formal educational programs. Rather, it is the integration and identification of interrelationships across six domains, spanning multiple technical discipline areas, within a complex system throughout the project life cycle. SAE-6906 [ref. 7] describes an HSI practitioner or HSI SME as "someone trained and/or experienced in HSI or the HSI domains who participates in the execution of the HSI program." While there is no single answer for every project, an HSI Lead must have experience with human-centered design, just as an SE must have experience with systems design to accomplish the role of system integrator. An HSI Lead will always be an HSI practitioner by definition of the lead role; however, an HSI practitioner will not always be an HSI Lead and may be providing HSI support to someone in the lead role. This will depend on the size, complexity, and risk classification of the project, which will dictate the size of the HSI efforts and team. For the purposes of this document, the term HSI Lead is used unless the statements pertain solely to an HSI practitioner function.

The HSI Lead is the person assigned by Engineering, in coordination with project management, who leads the HSI effort. The lead reports to program management, SE process managers, and/or other key stakeholders as defined by the PM. They assist project management in assessing HSI personnel needs and critical early-phase HSI efforts, based on the project's scale, mission, budget, schedule, and scope, and they work as a part of the design and development team to ensure that human-related design considerations are placed on equal par with hardware and software considerations during the design and development process. Ideally, the individual best suited to serve as an HSI Lead is someone who is trained in the HSI processes, understands how HSI works as a component of the overall NASA systems engineering process and has expertise in more than one of the HSI technical domains

HSI requires the participation of highly qualified and experienced personnel who understand how to integrate human performance and capabilities into research, design, development, and system implementation.

The demand for HSI practitioners will naturally grow as a result of improved HSI implementation and current and expected Agency policy and procedural changes. Along with the growing need for trained HSI practitioners, there is an accompanying need for Agency training, which is in development by the HSI community.

If there are questions regarding identification of an HSI lead or an HSI practitioner, program or line personnel should reach out to a Center Technical Authority (TA) Office (Engineering), Health and Medical, or Safety and Mission Assurance), or contact the Center representative(s) to the Agency's HSI Community of Practice (CoP) Core Team. The CoP core representatives can provide valuable information and recommendations to support programs and projects through the application of HSI and can help identify appropriately qualified personnel given project scope, requirements, and staffing constraints.

Suggested core competencies for an HSI Lead or practitioner, provided in Table 2.1-1, are based on the Handbook of Human Systems Integration [ref. 8].

Table 2.1-1. Core HSI Lead or Practitioner Competencies Compared with SE&I Competencies

HSI Competencies	**Systems Engineering and Integration**
Statistics	Acquisition process models
Sensory and Perceptual Processes	Requirements determination
Cognition and Decision Making	Systems design and management:
Physical Abilities and Limits	– Human-centered design
Anthropometry and Work Physiology	– Proposal development, and evaluation
Simulation Methodology	– HSI assessments
Human Systems Modeling	– Program/Project Management
Human Performance Measurement	Testing and evaluation:
Design of Displays, Controls & Workstations	– Measures of effectiveness and performance
Skill Acquisition	– HSI in test design plans
Personnel Selection	– HSI in test reports
Team Performance	HSI technology research and development
Environmental Health Hazards	Operations research and experience
System Safety	Integrated logistics support processes
Human Survivability in Extreme Environments	Safety engineering and management
Organization Design	Training approaches and methodologies
Analytical Techniques	Economic and cost analyses
Risk Management	

Additional significant responsibilities of an HSI Lead include: [ref. 9]

- Advocating for each of the HSI domains (See Section 2.2 for domain information).
- Applying HSI methodologies to NASA and contracted efforts in support of programs.
- Assisting domain personnel in planning domain activities.
- Facilitating execution of domain tasks and collaboration between domains.
- Making trade-offs between domains to optimize the attainment of HSI goals.

- Including all required and appropriate HSI requirements and trade-off analyses associated with Analysis of Alternatives and source selection.
- Optimizing the impact of domains on the project from the perspectives of performance, sustainability, and cost.
- Integrating the results of domain activities and analyses representing them to the SE, in support of programmatic design and cost decisions.
- Tracking, assessing, and providing status of HSI risks, metrics, issues, and opportunities.
- Conducting technical and programmatic tasks necessary to resolve HSI issues and concerns before each milestone decision review.
- Developing funding and resourcing requirements for effective HSI Program implementation, testing, and maintenance.

It is the responsibility of the HSI Lead to facilitate interactions internally between domains and related discipline functions, and externally between HSI and the rest of the project. The Lead should plan NASA HSI activities, requirements, and team structure, as well as understand the role that any prime contractor, or partner, engaged on the project will perform, particularly in terms of implementing HSI and HSI deliverables (See Section 5.2, Appendix A, and Appendix F for more information).
Accordingly, prime contractors, or partners, should also designate one of their personnel to function as their lead HSI Point of Contact (POC) who is able to lead their internal HSI interactions and planning, and coordinate with the HSI Lead of the program or project.
A clear vision of HSI efforts needed to support the particulars of the project is critical to developing a comprehensive, integrated HSI approach; delivering a return on HSI investment; and producing a system that will meet user needs from a human-systems and operations standpoint.

2.2 HSI Domains

HSI incorporates and integrates key human elements, referred to as domains. Successful and effective implementation of HSI depends on the integration and collaboration of all NASA HSI Domains, presented and defined in Table 2.2-1. Whether a domain is considered an independent discipline (e.g., Human Factors Engineering) or a combination of discipline activities (e.g., Maintainability and Supportability, Safety), successful HSI depends on the integration and collaboration across all HSI domains and related discipline activities. It is important to note that these domains have been defined for the purpose of HSI implementation in NASA projects and are intended to be integrated functions versus representing Agency functions or organizations.

Each domain has the potential to affect and interact with the other domains, making it critical to execute an integrated discipline approach. Additionally, decisions, changes, environmental disturbances, or new system constraints introduced into one domain will disturb the balance of interdependencies between the domains and potentially impact one or more of the other domains.

HSI integrates the domains to leverage and apply their interdependencies to attain an optimal system. By this process, domain interests can be integrated to perform effective HSI through trade-offs and collaboration. An understanding of how trade-offs among the domains occur and propagate through a system enables a clear understanding of the implications of the integration of the domains which subsequently can be used as a basis for making knowledgeable decisions (See Section 3.5.1 for additional information). For HSI to optimize total system performance (i.e., human + hardware + software + environment), the appropriate HSI domains should be engaged throughout the system life cycle.

Implementation of HSI processes and practices requires regular and frequent communication, coordination, and integration across the HSI domains providing human systems expertise.

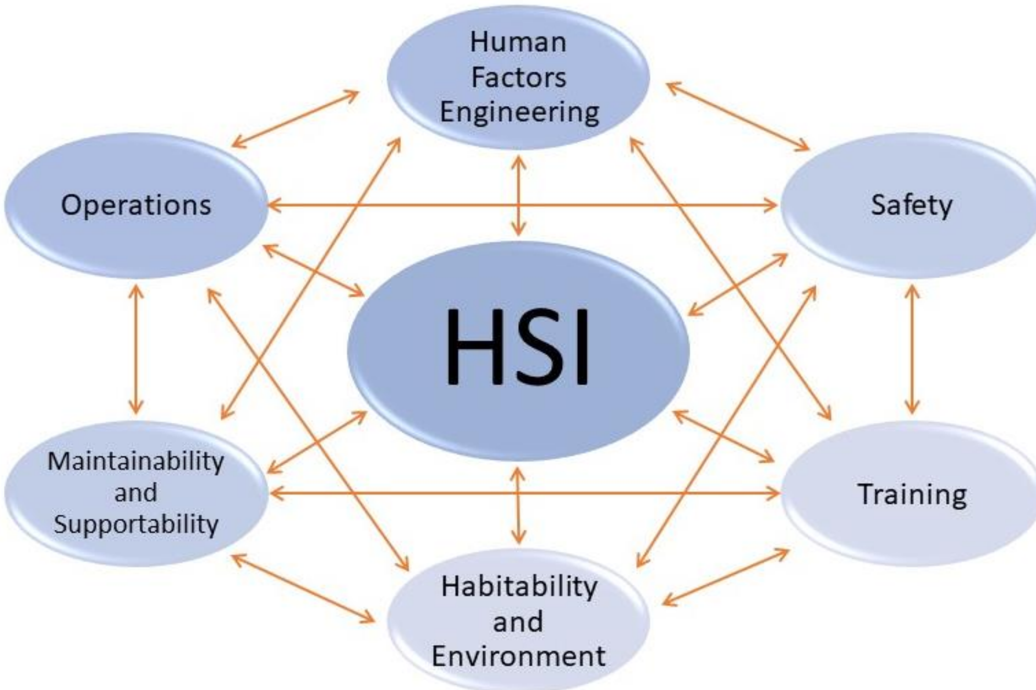

Figure 2.2-1. Sample 2-way Interactions Among NASA HSI Domains

Table 2.2-1. NASA HSI Domains, Definitions, and Examples of Expertise

Domain	Definition	Examples of Knowledge, Skills, and Abilities
Human Factors Engineering (HFE)	Designing and evaluating system interfaces and operations for human well-being and optimized safety, performance and operability, while considering human performance characteristics as they affect and are affected by environments and operating in expected and unpredicted conditions	• Human performance measurement • Anthropometry and biomechanics • Perceptual, sensorimotor, and cognitive processes • Task analysis • Human/Machine Function Allocation • Workspace, vehicle, equipment, and workstation design • Display and control design • Information structure, presentation, and communication • Workflow management • Procedure development • Decision support • System error prevention and recovery • Team dynamics • Organizational behavior • Human-in-the-loop (HITL) evaluations • Performance modeling • Impacts of stressors on performance (e.g., environmental, organizational, temporal)

Domain	Definition	Examples of Knowledge, Skills, and Abilities
Operations	Full life-cycle engagement of operational considerations into the design, development, maintenance and evolution of systems and organizational capability to enable robust, cost-effective mission operations for human effectiveness and mission success	• Operations Engineering • Operations process and tool design for personnel (ground and flight crew, operators and maintainers) • Control Room Operations • Communications and Data Interfaces and Constraints • Human/machine resource allocation • System Availability • Mission Operations • Resource modeling and complexity analysis • Procedure and timeline development • Human-automation teaming • Staffing/qualifications analysis • Integrated Operations Scenarios development
Maintainability and Supportability	Designing for full life cycle and simplified maintenance and accessibility, reliability, optimized resources, spares, consumables and logistics given mission constraints	• Aerospace Systems Maintenance and Housekeeping • Ground Maintenance and Assembly • Sustainability and Logistics • Reliability-Centered Maintenance • Maintenance task analysis (tools, training, manpower) • Maintenance Manuals/Documentation • System Availability
Habitability and Environment	Ensuring system integration with the human through design and continual evaluation of internal/external living and working environments necessary to sustain safety, human and mission performance, and human health.	• Environmental Health • Radiation Health • Toxicology • Nutrition • Acoustics • Lighting • Architecture • Ingress/Egress and translation paths • Restraints • Crew Health and Countermeasures • EVA • Behavioral Health • Life Support Systems • Physiology and Anatomy • Medical operations • Occupational safety and health
Safety	Implementation of safety considerations across the full life cycle to reduce hazards and risks to personnel, system, facilities and mission.	• System Safety • Safety Analysis • Quality Assurance • Quality Engineering • Software Assurance • Survivability • Human rating • Risk Management (identification, analysis, and mitigation)

Domain	Definition	Examples of Knowledge, Skills, and Abilities
		• Safety Culture • Institutional Safety • Occupational safety and health • Aviation Safety • Fire Protection • Nuclear Flight Safety • Payload Safety • Pressure Systems • Planetary Protection • EEE Parts • Government Industry Data Exchange Program • Micrometeoroids and Orbital Debris
Training	Design and implementation of effective training methods and resources to maximize human retention, retrieval and transfer, proficiency, and effectiveness to successfully accomplish expected an unexpected mission tasks, properly operate, maintain, and support the system and mission.	• Training Needs Analysis • Task skill knowledge assessment • Instructional Design/Methods • Training Facility Development • Training manuals/documentation • Training Fidelity • On-board Training (OBT) • Simulations • Training for nominal and unexpected events

As stated above and depicted in Figure 2.2-2, each HSI domain has the potential to affect and interact with the others, making an integrated discipline approach critical. With six domains, there are 15 pairs of two-way interactions, not to mention the addition of three-way, four-way, etc. that would be impossible to graphically illustrate; therefore, interactions depicted here are examples and not all-encompassing.

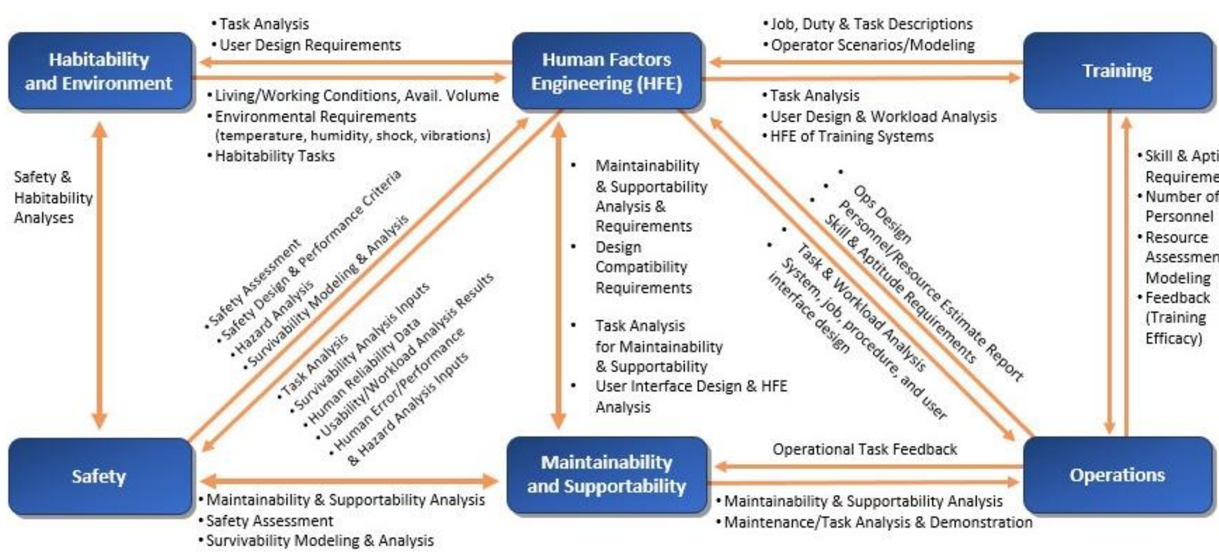

Figure 2.2-2. HSI Domains and Sample Interactions

In the 2019/2020 timeframe, DoD reassessed its defined HSI domains and revised the set from nine identified areas to seven. DoD Instruction 5000.02, Enclosure 7, identifies the following seven domains:

Human Factors Engineering, Safety and Occupational Health, Manpower, Personnel, Training, Force Protection and Survivability, and Habitability [ref. 10]. The NASA and DoD missions differ in many ways, and each organization's HSI approach has been tailored to meet its mission needs. NASA's HSI domains are less focused on the large workforce and diverse skill sets required for DoD mission objectives, but HFE remains a significant domain for DoD and NASA HSI processes.

Of approximately 100 positions within the U.S. Army that align to HSI missions, the types of personnel performing these duties break down as follows: Engineer (Human Factors) (10); Engineering Psychologist (24); Engineering Research Psychologist (4); Psychologist (11); and Research Psychologist (59) [ref. 11]. So, while HSI is not synonymous with HFE, the skill sets within the HFE discipline are significant contributors to the accomplishment of HSI within programs and projects.

HFE is to HSI much as a specific engineering discipline is to SE. Systems engineers have the broad system perspective and, at a high level, coordinate the other engineering teams, ensuring that requirements flow down, interfaces are agreed upon, trade-offs are made analytically, and the various components come together to form an integrated system. Design and development of specific system components are conducted by the relevant engineering disciplines (e.g., mechanical, electrical, materials, software). The systems engineer is not required to know how to design any system component but does need to know how the efforts interrelate and form a complete system solution. In the same way, the HSI Lead coordinates the HSI domains, ensuring system requirements are identified and flowed down from all applicable sources. SMEs are appropriately involved in design decisions, trade-offs are made analytically, and the integrated system fully considers the human components.

The HSI Lead formulates a team with SMEs from each domain discipline. Recommendations from all HSI domains are integrated into reports and recommendations from the HSI Lead to SE and will have a strong influence on mission success and operations costs, working collaboratively with the principles, goals, and metrics of the other domains and interacting with system designers and developers.

2.2.1 Human Factors Engineering

HFE enhances the comprehensive design and evaluation of system interfaces and operations for human well-being and optimized safety, performance and operability while considering human performance characteristics (sensory, perceptual, cognitive, physical, and team dynamics) as they affect and are affected by environments while operating in expected and unpredicted conditions. HFE produces safe and effective human-system interfaces, facilitating performance in the operation, maintenance, support, and sustainment of a system. Human Factors Engineers are responsible for representing the human in the design team in the same way that electrical engineers (EE) represent the electrical aspects of the design. They accomplish this in a similar manner; just as an EE is understood to have knowledge of electronics that other engineers lack, the HFE has knowledge of human behavior, capabilities, and constraints that other engineers do not. This is accomplished through:

a. Developing or improving all human interfaces of the system so the design is consistent with relevant human engineering standards.
b. Achieving required effectiveness of human performance during system nominal, off-nominal and unexpected operations, maintenance, control, and support (human effectiveness requirements are often implicit in reliability and maintainability requirements).
c. Conducting analyses (primarily task analyses, but also function allocation, human error analysis, and others) and coordinating results with overall systems engineering and the rest of the HSI Team.
d. Evaluating system design alternatives and issues, including cost-benefit implications addressed in trade-off studies and white papers to help ensure human factors are appropriately prioritized and

addressed and recommended alternatives achieve human factors requirements.

Additionally, undesirable characteristics can be reduced or eliminated when HFE principles are applied to the design and development of systems, such as:

- Emphasizing matching human capabilities to reduce or eliminate systems that strain cognitive, physical, sensory and perceptual abilities, or workload-intensive tasks that exceed user capabilities.
- Creating effective interfaces or systems to offset unnecessary complexity and avoid extensive training requirements.
- Avoiding design-induced human performance issues, which may lead to user errors, mission-critical errors, safety/health hazards, and reliability issues, by eliminating error traps.
- Designing error mitigations that do not interfere with recovery techniques, since systems rely on human resilience to handle unexpected events.

Note: The highlighted box below points to relevant case studies for this section that can be found in Appendix D. These boxes appear throughout the document to aid in understanding the material and provide the reader with greater insight into the importance of HSI.

CASE STUDIES: Human Factors Engineering

D.3 Expert Knowledge of Human Performance: Effective Countermeasure for Launch Vehicle Display Vibration

D.5 Training, Simulation, Design and Human Error: The Virgin Galactic Spaceship Two Mishap

2.2.2 Operations

The operations domain involves the full life-cycle engagement of operational considerations into the design, development, maintenance, and evolution of systems and organizational capability to enable robust, cost-effective mission operations for human effectiveness and mission success. Operations includes operability considerations and human effectiveness for flight crews, ground and maintenance crews, and test personnel to drive system design and development trades for function allocation, automation, and autonomy.

Automation refers to a system with programmed characteristics that offload human tasks, whereas *autonomy* refers to a system that performs tasks independent of human interaction. This includes the design of communications and data interfaces and constraints. Operations processes design for ground and flight crews, human/machine resource allocation, mission operations, resource modeling and complexity analysis, flight operations, procedure development, crew time, and staffing/qualifications analysis.

2.2.3 Maintainability and Supportability

Maintainability and supportability requires designing for the full life cycle, including assured maintenance and support, within mission constraints. Accessibility, reliability, optimized resources, spares, consumables, and logistics are all terms in the analysis performed by the M&S domain for the HSI Lead. It includes a strong relationship to reliability and maintainability (R&M) and the safety domain, and addresses design, development, and execution of simplified maintenance given corresponding mission constraints and objectives. These include aerospace systems in-flight maintenance and housekeeping, ground maintenance, and assembly, as well as maintenance task analysis, or designing for efficiency in the tools, training, and manpower necessary to maintain and sustain the system. It also encompasses maintenance manuals and documentation and system availability.

2.2.4 Habitability and Environment

The habitability and environment domain ensures system integration with the human through design and continual evaluation of the internal/external living and working environments necessary to sustain safety, human/mission performance, and health. Habitability factors contribute directly to personnel effectiveness and mission accomplishment. Habitability factors apply to all work environments, including ground and testing facilities and control rooms, as well as in-flight and surface vehicles and habitats. Examples include lighting, space, ventilation and sanitation; noise and temperature control in space- and aircraft, vehicles, architectural arrangement and configuration, and facilities (i.e., heating and air conditioning); ingress/egress and translation paths; and environmental health. Habitability factors include living and working conditions that result in levels of personnel morale, safety, health and comfort adequate to sustain maximum personnel effectiveness, and support mission performance.

The HSI Lead should work with habitability and environment SMEs to establish requirements for the physical environment as well as living and working environments to ensure sustaining performance requirements and mission effectiveness.

While a system, facility and/or service should not be designed solely around optimum habitability factors, these factors cannot be systematically traded off in support of other system elements without eventually degrading mission performance.

2.2.5 Safety

The safety domain involves the application of engineering and management principles, criteria, and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time, and cost throughout all phases of the system life cycle. The safety domain concerns operating and maintaining the equipment/system in a manner that minimizes risk of injury or death to personnel. Adverse conditions may occur when the system is functioning in either a normal or an abnormal manner. Every design decision may affect system safety to a greater or lesser degree and may pose risks to humans from damage, malfunctions, or failure to recover from unexpected events. The safety domain lead creates analyses that identify these risks and works with the HSI Lead to develop mitigations. Whenever possible, these mitigations will include design modifications that improve system safety.

Safety focuses on system design characteristics that minimize the potential for mishaps that could cause death or injury to humans, threaten system survival and/or operation, or cause cascading failures in other systems. It also strives to create systems that are safety-resilient. Prevalent issues include factors that threaten safe system operation; pressure extremes; and control of hazardous energy releases, such as mechanical, electrical, fluids under pressure, ionizing or non-ionizing radiation, fire, and explosions.

Occupational health factors should also be considered. These system design features minimize the risk of injury, acute or chronic illness or disability, and reduced job performance of personnel who operate, maintain or support a system. Prevalent issues include noise, chemical safety, atmospheric hazards (including those associated with confined space entry and oxygen deficiency), vibration, ionizing and non-ionizing radiation, and human factors issues that can create fatigue, chronic disease, and discomfort (such as repetitive motion injuries). Many occupational health problems, particularly noise and chemical management, overlap with environmental impacts.

Safety analyses and lessons learned can aid in developing design features that prevent safety hazards to the greatest extent possible and manage those safety hazards that cannot be avoided.

CASE STUDIES: Safety

D.2 STS-93 Launch: Damage Incurred and Undetected During Repeated Refurbishment and Maintenance Contributed to In-Flight Anomaly

D.3 Expert Knowledge of Human Performance: Effective Countermeasure for Launch Vehicle Display Vibration

D.4 Cumulative Effects of Decision Making, Management Processes and Organizational Culture: Genesis Probe Mishap

D.5 Training, Simulation, Design and Human Error: Virgin Galactic Spaceship Two Mishap

2.2.6 Training

Training the human component of the system provides the opportunity to acquire, gain, or enhance knowledge and skills, and concurrently develop cognitive, physical, sensory, team dynamics, and adaptive abilities to conduct joint operations and achieve maximized, sustainable system life cycles. Training is accomplished through any activity that enables people (e.g., operators and maintainers) to acquire or enhance their knowledge, skills, and attitudes (KSAs). The training domain involves design and implementation of effective training methods and resources to maximize human retention, proficiency, and effectiveness to successfully accomplish mission tasks, properly operate, maintain, and support the system and mission. Effective training solutions equip personnel with the KSAs required for effective, efficient, and safe systems operation at a fiscally sustainable cost. Training systems implement a broad range of concepts, strategies, and tools to accomplish this purpose, such as computer-based and interactive courseware, simulators, and embedded training functions.

The goal of training for new systems is to develop and sustain well-trained operators, maintainers, and others that have knowledge and skills to efficiently and safely perform their roles in system context to enable mission safety and success. Training is needed as an HSI domain because as system complexity increases, design decisions can have direct impacts on the amount of training needed by operators. As human exploration missions increase in duration or go beyond low-Earth orbit, onboard training must be designed in; attempts to add it later will inevitably lead to failures in effectiveness, with direct negative impacts to safe operations. The training domain lead provides analyses to the HSI Lead that are in turn used in system trades by the HSI Lead and SE.

Training planning should be initiated early in the project life cycle and should also be considered in collaboration with the other HSI domains to capture the full range of human integration issues for consideration within the HSI and SE processes. Early considerations should characterize specific system training requirements and identify any key performance parameters (KPPs). See Section 5.2.2.8 for additional information on KPPs.

As the system design matures, training requirements should be developed to enhance operator capabilities. These may include requirements for expert systems, intelligent tutors, embedded diagnostics, virtual environments, and embedded training capabilities.

CASE STUDIES: Training

D.2 Damage Incurred and Undetected During Repeated Refurbishment and Maintenance Contributed to In-flight Anomaly During STS-93 Launch

D.4 Cumulative Effects of Decision Making, Management Processes, and Organizational Culture: The Genesis Probe Mishap

D.5 Training, Simulation, Design and Human Error: The Virgin Galactic Spaceship Two Mishap

D.7 Inadequate Training, Procedures, Interface Design and Fatigue: The Collision between Navy Destroyer John S. McCain and Tanker Alnic MC

D.8 The Cost of Untested Assumptions About Human Performance: The Case of the B737MAX

2.3 Key Concepts of HSI

As described in the Expanded Guidance for NASA Systems Engineering [ref. 12], the goal of the HSI product life cycle is to balance total system safety and effectiveness and ensure mission success through iterative attention to efficient interaction of hardware and software design with the total system's most critical, versatile, and variable element: the human. HSI is a set of process activities that ensure (1) the systems design supports and includes personnel in an integrated perspective on total system performance, reliability, and safety; (2) the physiological, cognitive, and social characteristics of personnel are addressed in systems development; and (3) system designs are standardized and consistent across all products HSI supports, in areas such as user interfaces, procedures, and training. For additional information on the products that HSI supports and develops, see Table 5.3-1.

HSI activities include management and technical processes that work within systems engineering and complementary Safety and Mission Assurance (SMA) and Heath and Medical processes and methodologies to ensure successful outcomes. Humans bring unique capabilities to any project—e.g., real-time decision making, creative thinking, an ability to understand the big picture, and complex communication ability. Humans are the most resilient part of any system and can adapt the system if even remotely possible; however, human error can occur. Acknowledgment of these limitations and capabilities, in the form of early planning and system design, greatly enhance the chance of mission success. Success in system design hinges upon the designers' ability to appropriately account for human performance. Neither resilience nor errors are immutable human properties—both are influenced by system design and the operational context. By understanding human capabilities, system design and system operations, HSI implementation can help to avoid error traps, enhance human reliability, and support positive human contributions to system performance.

HSI relies on four key concepts to ensure successful implementation throughout the project life cycle. The importance of these concepts is exemplified in the HSI case studies in Appendix D, which describe successes and failures in instantiating these concepts:

1. **HSI must be considered and established in program and project planning early and applied iteratively throughout the development life cycle, from pre-Phase A through to Phase F** (see Figure 2.3-1, NASA Project Life Cycle). Early application of HSI provides the best opportunity to maximize LCC efficiency and total system performance (see Section 3 for additional LCC details). HSI requirements and goals must be developed in phase with system capability-based requirements. HSI requirements will drive HSI metrics and embed HSI goals within the system design. After a system is designed, implementation of HSI oversight or workarounds that result from the lack of HSI during design can become costly.

2. **HSI includes all personnel that interface with a system in the expected environment at any and all life-cycle phases**. End users, designers, assemblers, maintainers, ground controllers, logistics personnel, sustaining engineers, trainers, etc. are all part of the system. Unlike the other two components of a system, humans are not subject to engineering processes. Moreover—and importantly—the interactions derive from their capabilities and limitations during system operations. These interactions are only minimally understood and predicted by design engineers. For this reason, the HSI Lead and the associated domain leads are responsible for knowledge of human characteristics and analyses that characterize the interactions in the expected environments and assuring that those characteristics are accommodated by the designed portions of the system. Each class of personnel requires resources that must be accounted for in design, cost planning, and operations.

3. **Successful HSI depends upon integration and collaboration of multiple domains.** Prior to the concept of HSI, separate human-centered domains had to interact with project management structures as independent disciplines due to the lack of a coordinated approach to including the human element in system design and operation. Design decisions have integrated effects and therefore require integrated analyses. For example, solutions that may be recognized by design engineers as requiring HFE analyses usually also have consequences for safety, M&S, training, and other domains. It is the responsibility of the HSI Lead to recognize these and integrate the inputs from all affected domains. Proper implementation of HSI helps all human-centered domains have a more assured, coordinated voice in system design and engineering. It is expected that the HSI Lead will resolve or mitigate conflicting inputs related to requirements tied to the human system before project management needs to engage. Via internal integration, HSI domain interests can better participate in project trade studies and design collaboration. Effective HSI implementation should integrate the domains, leveraging and applying their interdependencies to attain optimal system design.

4. **The system comprises hardware, software, and human elements, as well as the data and procedures needed to operate and maintain it within an environment.** The roles and responsibilities of each operations component must be allocated early in the design to ensure the operational system does not place undue demand on the human. As demonstrated in several case studies in this handbook, the human element is critical to the overall performance, effectiveness, and efficiency of the total system.

   The initial paragraph of NPR 7123.1C states: "NASA SE is a logical systems approach performed by multidisciplinary teams to engineer and integrate NASA's systems to ensure NASA products meet the customer's needs. Implementation of this systems approach will enhance NASA's core engineering capabilities while improving safety, mission success, and affordability. This systems approach is applied to all elements of a system (i.e., hardware, software, and human) and all hierarchical levels of a system over the complete project life cycle." The NASA Project life cycle, as defined by NPR 7120.5, is shown in Figure 2.3.1. Additional information on HSI across the NASA Project Life Cycle can be found in Section 5.4 and Appendix B.

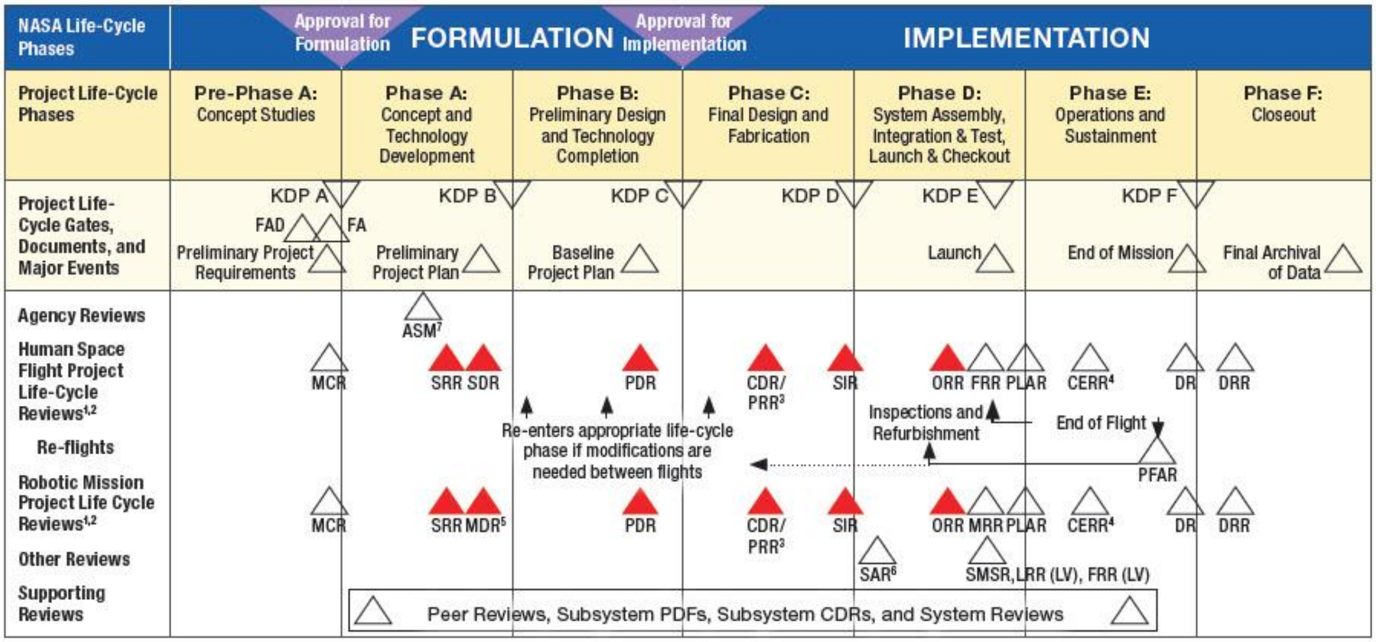

Figure 2.3-1. NASA Project Life Cycle (NPR 7120.5)

3.0 Impacts of Human Systems Integration

Shaver and Braun [ref. 13] identified a range of benefits resulting from increasing and decreasing cost-related aspects of the development, manufacturing, distribution, sales, and support activities of human factors and ergonomics that is foundational to HSI. The list below is composed of HSI impacts, some of which are based on the Shaver and Braun return on investment assessment.

Effective HSI application results in:

- Improved safety and health, including fewer accidents and less lost time.
- User satisfaction, trust, and loyalty, which increase the probability of mission success, particularly in stressful or critical operations.
- Ease of use, resulting in reduced incidence of user errors and higher resilience (error recovery).
- Ease of learning, together with reduced training time, to give higher training retention.
- Higher productivity and work effectiveness.

Failure to apply HSI results in greater potential for:

- Risk to human life, which could terminate the current mission and threaten future missions as well as the Agency's reputation.
- Risk of major accidents that threaten missions and significantly increase cost.
- Mishaps, injuries, and illnesses that reduce mission effectiveness and threaten success.
- Higher error rates.
- Greater training burden—time and personnel.
- Increased development costs.
- Costly redesigns and operational workarounds.
- Higher maintenance support and service costs.

Many of these impacts are highlighted in the case studies provided in Appendix D. These show both positive and negative impacts of HSI application and implementation (or lack thereof) in mission programs and projects. Table 3.0-1 correlates each case study to HSI impacts.

Table 3.0-1 HSI Impacts Mapped to Case Studies

	D1. Shuttle Ground Processing	D2. STS-93 Anomaly	D3. Display Vibration	D4. Genesis Probe Mishap	D5. Spaceship Two Mishap	D6. F-119 Engine Development	D7. Navy Destroyer Collision	D8. Boeing 737-Max
Successful HSI application results in:								
Ease of use			X			X	X	X
Ease of learning & reduced training time						X		
Higher productivity & effectiveness						X		
Failure to apply HSI results in greater potential for:								
Mishaps, injuries, illnesses		X		X	X		X	X
Higher error rates		X		X	X		X	X
Higher training burden		X			X		X	
Higher development costs	X							X
Need for redesigns & workarounds	X			X				X
Higher maintenance support & service costs	X							

3.1 Life-Cycle Cost Effect of HSI

One goal of HSI is to reduce overall project cost. HSI Leads and practitioners will use the tools and techniques described in this handbook not only for effective human-system design, but also for cost efficiency in HSI areas. Although overall system safety, effectiveness, and efficiency are goals of the HSI process, the potential for LCC savings led to HSI becoming mandatory in the DoD and other federal agencies and is an important benefit to NASA as well.

The NASA HSI Lead should help the PMs and Systems Engineers keep the cost, schedule, and performance of HSI in view. The lead is the ultimate human element discipline integrator who must translate design decisions into project common currencies, such as LCC, downtime required for maintenance procedures, and total system autonomy from logistics and resupply. Human element life-cycle operations generally manifest themselves in numbers of people, specialized skillsets, and the necessary resources for training.

It is not within this handbook's scope to provide a "how to" for calculating cost per project, but the effect of HSI on costs of established processes and project decision-making is important to consider. NASA/SP-2014-3705 [ref. 13] is an excellent resource for project cost management guidance. The NASA Space Flight Program and Project Management Handbook also refers to the NASA Cost Estimating Handbook [ref. 15]. See "Cost Estimation of HSI" [ref. 16] for specific guidance, including applying the Constructive Systems Engineering Model (COSYSMO) tool for HSI.

From an HSI investment standpoint, the users of NASA hardware and software expect products that can be used safely and effectively to accomplish a given mission with minimal errors and maximum efficiency. They also expect the development community to have addressed user needs and capacities as intrinsic to system effectiveness. These expectations may not be met without a unified and integrated HSI investment.

As noted earlier, the DoD made HSI mandatory when faced with alarming, unanticipated cost escalation in deploying new weapon systems and finding expensive systems unusable by warfighters. Much of the unplanned cost growth was due to personnel costs in the systems operations phase—i.e., operating, maintaining, and logistically supporting systems required more people and more advanced skills than expected. Faced with the awareness of cost growth in the human elements needed to make and keep systems operational, HSI was a tool to focus on systems' full LCCs—conception through operations—starting at the outset of new programs and projects. Figure 3.1-1, adapted from the INCOSE Systems Engineering Handbook [ref. 17] and the HSIPG [ref. 18], shows that the LCC of a project is "locked in" early on.

Although early pre-determination of LCC may apply to any system design element neglected early in the project, it is particularly noteworthy for HSI, since hardware and software system designers often focus on technology development without considering the human role in the system's operation.

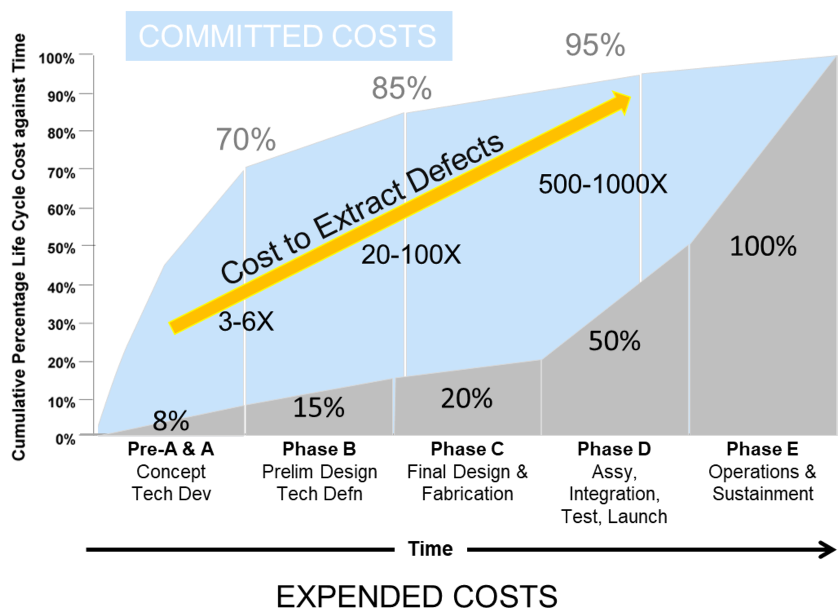

Figure 3.1-1. LCC with Overlay Showing Locked-in Costs

As a project progresses through its life cycle, the cost of making design changes increases dramatically. Future costs are locked in early in the course of decision-making; therefore, alternative design concepts should be iteratively evaluated for their LCC impact or failure to find more effective alternatives. Growth of personnel costs during the operations phase is possible and even probable if not evaluated early. System designers must not assume that any design solution can be made usable by adding personnel, skills, and training, because these resources are neither infinite nor free. Rather, designers must assume human resources are as limited as any other project asset. Costs can also increase as a result of assumptions about human performance that are not achievable in the intended operational environment, or by failing to include HSI domain considerations in design trade analyses to appropriately bound out-year cost escalation in operations, maintenance, and logistics expenditures. Properly applying HSI processes should reduce LCC by emphasizing efficient human performance goals in system operations; during system design; and through development, test, and evaluation.

Few case studies fully evaluate the LCC impact of HSI for past programs or the return on investment (ROI) of effectively applying HSI. The true cost of a path not taken is difficult, if not impossible, to obtain. It is rare that the outcome of a program in which HSI processes were applied can be compared to the outcome of an identical program where they were not. However, adding HSI-oriented alternatives to the SE hardware/software trade space can provide another means to positively impact and evaluate LCC through the SE trade study process. This is covered in detail in Section 3.5.1, *Identifying Human-Centered Trade-offs*.

Particularly in the earliest stages of a new project, the HSI Lead may find it necessary to justify the value of providing targets and tracking costs for the human elements that make a system functional throughout its life cycle. Standing on requirements documents alone may not carry as much leverage as being able to cite examples and case studies where HSI makes (or could have made) a difference in the success or failure of missions and projects. HSI case studies are provided in Appendix D.

CASE STUDIES: HSI Impact on LCCs

D.1 Inadequate Consideration of Operations During Design: Shuttle Ground Processing

D.6 Effective Culture, Requirements, and Trade Studies: The Reliable and Maintainable F-119 Engine

D.7 Inadequate Training, Procedures, Interface Design, and Fatigue: The Collision Between Navy Destroyer John S. McCain and Tanker Alnic MC

D.8 The Cost of Untested Assumptions About Human Performance: The Case of the B737MAX

3.2 Return on Investment

Today's systems are becoming more complex and increasingly more difficult to design, develop, test, integrate, and operate using traditional techniques and methods. Users of modern systems expect, even assume, that products can be used and maintained safely and effectively without extensive training or extraordinary measures. They also expect the development community to address human needs and capacities as intrinsic to system effectiveness. These expectations may not be realized without a unified and integrated HSI effort. This requires an investment of time, resources, and personnel.

A manager trying to improve system performance may adopt a short-term focus on the need to stay on schedule and within budget. The result may be an on-budget but suboptimal system that cannot be deployed safely and effectively without costly corrections and rework.

The following example from Curiosity Mars Rover operations illustrates the concept:

Example: Implications of Instrument Design Choice

The Curiosity Rover executes a command sequence covering one Martian day of activities, without real-time monitoring or operator intervention. These daily activities are supported by three mast-mounted instruments: a ChemCam spectrometer, MastCam stereo imager, and NavCam stereo imager. These instruments can be destroyed by sufficient dwell time in the sun, so the initial design of the ChemCam instrument included an actuated opaque cover. However, the cover was removed from the design out of concern for potential actuator failure during the mission, which would render the instrument unusable.

As a consequence of this design change, operations teams for all mast-mounted instruments must now analyze all observations for "sun safety." This places another demand on an already time-constrained process. Sun safety is dependent on Mars time of day, rover attitude, mast pointing, and the timing of successive observations. Sun-safety determination was initially a manual process during Mars surface missions. New software tools later simplified the assessment, and new on-board software for ChemCam was developed as redundant protection against sun damage. This design choice resulted in increased operating costs, increased risk of damage to the ChemCam instrument, and new constraints on MastCam and NavCam observation designs.

Applying a robust HSI program early in system development and acquisition allows the program manager to maximize overall ROI in several important ways. Implementation of effective HSI practices and concentration on reducing overall life-cycle budget will tend to optimize system performance, reduce LCCs, provide more usable systems, and minimize occupational health hazards and opportunities for mishaps.

CASE STUDIES: Return on Investment

D.1 Inadequate Consideration of Operations During Design: Shuttle Ground Processing

D.2 STS-93 Launch: Damage Incurred and Undetected During Repeated Refurbishment and Maintenance Contributed to In-Flight Anomaly

D.3 Expert Knowledge of Human Performance: Effective Countermeasure for Launch Vehicle Display Vibration

D.5 Training, Simulation, Design and Human Error: Virgin Galactic Spaceship Two Mishap

D.8 The Cost of Untested Assumptions About Human Performance: The Case of the B737MAX

Given that human performance exerts such a significant effect on system effectiveness, the only question is whether HSI will be paid for most affordably in advance or at much greater expense after a newly developed system reveals significant problems. The earlier an HSI investment can be made, the greater its return. The longer the wait to implement HSI, the more negative the impact on total LCC. However, there are benefits to incorporating HSI at any point in design maturity, as long as it precedes the final design. Generally, 50% of LCC (sometimes more) is already locked in by the Preliminary Design Review (PDR). By Critical Design Review (CDR), the opportunity to have a meaningful effect on LCC is nearly gone. The Air Force has reported that HSI investment typically costs 2%–4.2% of total acquisition cost and leads to a ROI of 40 to 60 times the investment [ref. 1].

Some key ROI opportunities are:

- Analysis of Alternatives (AoAs), trade-off studies, HSI tool use—design optimization.

- Design for reliability, availability, maintainability, and total systems performance.
- Design trade-offs to reduce hardware/software changes during research and development, test, and evaluation.
- Task analysis, functional analyses, and allocations—workload reduction.
- Design simulation and emulation—reduction of cost to prepare for test and evaluation.
- Full mission simulation—optimization of system to facilitate successful test.
- Elimination of most required hardware and software design changes prior to full operational capability.

3.3 Investment in HSI

HSI is quickly gaining respect as an affordable and viable capability within NASA. The Army, Navy, Federal Aviation Administration (FAA), and private industry (for example, Apple and their investment in user experience [ref. 19]) have also gained considerable experience in making the investment required to perform quality HSI from start to finish as part of development and acquisition programs.

According to MIL-HDBK 46855A [ref. 20], the values of HSI are best demonstrated by the positive and negative results of HSI activities. Money and time are required to recoup overall savings and increased total system performance, safety, and user satisfaction. The lack of HSI within a system usually results from shortcomings that require costly redesign, produce substandard system performance, or trigger system failures that can endanger life and equipment. Some problems can be resolved but may be more costly after the fact. An abundance of research on the benefits and costs of investing in HSI attests to the necessity of early implementation before a destructive situation occurs. As stated previously, integration is the key to meaningful savings through HSI, and optimal integration requires high-level coordination among domain owners, facilitated by an HSI team working to obtain optimal solutions.

Cost benefits of utilizing HSI during acquisition planning include improved manpower utilization, reduced training costs, reduced maintenance time, and improved user acceptance and performance. Improved operational performance can result in fewer delays, and improved design trade-off decisions can reduce LCCs and decrease the need for redesigns and retrofits. Program managers' decisions can affect LCCs and mission capabilities that may not be realized until decades later. HSI domains are not always obvious to a project manager as research and development funding is being established. However, they can quickly become a large part of what needs to be addressed as projects move through the system life cycle. Paying proper attention to these discipline areas up front can save upward of 40%–65% of project funding further down the pipeline. Some ways to mitigate risk in this area are to consider the HSI investment general guidelines below and follow the practices laid out in this handbook.

General Guidelines for HSI Investment

- ✓ Identify targets for LCC optimization and focus.
- ✓ Work closely with teams and program management to identify HSI high value areas that may impact critical programmatics, especially performance.
- ✓ Begin planning for trade-off assessments between and within HSI domains.
- ✓ Plan HSI investment, and work closely with teams and SMEs to identify best investment options.

As a NASA capability, HSI should strategically strive to identify consistent KPPs that may become common HSI currency across programs and projects. Consistent KPPs will not only help clarify basic duties required of the HSI Lead and of a successful HSI engagement but also help build a database with incorporation of lessons learned that could demonstrate the ROI of HSI.

Large and successful programs and/or projects typically become long-lived with extended operations phase(s), often with modifications to extend original objectives and systems life, add new capabilities or mission objectives, and accommodate unexpected behaviors. Extensive systems upgrades or refurbishment often re-start the SE process at an early life-cycle phase, usually Pre-Phase A. The HSI Lead can use the HSIP, discussed in Section 5.1.2.5, to document specific HSI goals based on lessons learned to ensure those goals continue to influence design.

CASE STUDY: Investment in HSI and Affordability

D.8 The Cost of Untested Assumptions About Human Performance: The Case of the B737MAX

3.4 Affordability

Improving design methods for affordability is critical for all projects and should be considered early in the life cycle. The INCOSE Affordability Working Group defined affordability as:

> "The balance of system performance, cost, risk, and schedule constraints over the system life while satisfying mission needs in concert with strategic investment and organizational needs."

By anticipating operational difficulties and designed-in ways to avert them, the HSI Lead, together with project management, can make a system more affordable to own and operate. Even before development begins, affordability plays a key role in identifying capability needs. When anticipating a new system, HSI should be considered as soon as it becomes apparent that the system's performance, affordability, and mission success will depend on the human component of the system and how efficiently, effectively, and safely they will perform. For this reason, HSI should be considered for every system since much of the total cost will go to training, accommodating, sustaining, and supporting the people who will operate and maintain it. Affordability should be incorporated into all programmatic decisions, as sound affordability practices have proven to be highly beneficial when developed and implemented as part of complex programs and projects.

Per the NASA Cost Estimating Handbook [ref. 21], an affordability analysis is often part of the trade study analysis and ensures that the final system can be owned, operated, developed, and produced at a cost that meets previously established funding (or best value) constraints while still meeting all approved requirements. Affordability is a continuous, overarching process applied throughout the project life cycle that ensures a program/project is doing the following:

- Optimizing system performance for the total LCC while satisfying scheduling requirements and managing risks.
- Acquiring and operating affordable systems by setting aggressive yet achievable cost objectives and managing those objectives throughout the full program/project life cycle.
- Balancing between cost objectives and mission needs with projected out-year resources, taking into account anticipated product and process improvements.
- Maintaining cost as a principal input variable in the program/project structure and in the design, development, production, operation, and support of a system.
- Emphasizing cost as more of a constraint, and less of a variable, in the process of developing and supporting affordable systems once system performance and cost targets are determined.

Much of the LCC associated with NASA's human space systems can occur during program/project operations and support. For robotic NASA missions, most of the mission cost is typically incurred during Phases C and D. Therefore, careful attention to affordability, particularly by establishing an affordability process and methodology in early program/project phases, will help NASA maximize cost savings, define best value solutions to top-level requirements, and reduce future program/project operations and sustainment costs. Affordability is achieved by establishing top-level affordability goals that then flow down to projects and challenging unaffordable requirements through life-cycle, cost-driven trade studies.

3.5 HSI in Trade Studies

An important HSI goal is ensuring that requirements relative to the HSI domains for a system (or system of systems) are satisfied within the constraints of performance, LCC, and development/delivery schedule. NASA system of systems (e.g., aircraft, space vehicle, compressor station facility) are inherently complex, with subsystems such as flight decks, life support systems, and machinery spaces, and may require a variety of context specific HSI trade-offs. A process-oriented HSI approach explicitly recognizes the need to balance requirements and make trade-offs. Decision-makers use trade studies throughout the project life cycle to select the most acceptable solution from a set of proposed solutions. The primary purpose of a trade study is to achieve system goals and objectives within the project constraints.

The focus is to perform objective comparisons of all reasonable alternatives and select the alternative that best balances criteria such as system performance, cost, schedule, reliability, safety, and risk. Because the human is a critical system component, some project design decisions must consider the human performance impact on total system performance and LCC. Thus, these decisions must be made within HSI domains, between HSI domains, and/or between HSI and other project elements (e.g., costs, schedule, risk), and the best alternative is sometimes unclear. An alternative that is optimal in one or more ways may also have one or more drawbacks; trade-offs must be made to select the option that will best meet project needs. For example, the HSI domains of HFE and training could suggest different approaches if designing a more intuitive user interface will be more costly to build but result in reduced training time and reduced training costs.

HSI can facilitate identification of risks and trade-offs, articulate their impacts if left unaddressed, and suggest alternative approaches to remedy gaps/shortfalls and optimize total systems performance. Sound application of HSI principles will minimize added costs that result when systems must be modified after implementation to correct performance and safety issues. A trade-off study is not done just once at the beginning of a project. Trade-offs are made continually throughout a project, when creating team communication methods, selecting components, choosing implementation techniques, designing test programs, and maintaining schedules.

Analysis has shown that trade-offs of usability requirements can be made during the systems engineering process. For example, poor attention to good HFE, perhaps motivated by acquisition budget/schedule constraints, can lead to systems with poor usability. In this case, higher levels of personnel resources would then be needed to achieve operational effectiveness, thereby increasing downstream operations and maintenance costs.

CASE STUDY: Importance of HSI in Trade Studies

D.6 Effective Culture, Requirements and Trade Studies: The Reliable and Maintainable F-119 Engine

Starting early in the acquisition process, continuous cost, schedule, and performance trade-off analyses can help to achieve cost and schedule reductions. Trade-offs are not unique to HSI but trading human issues against equipment issues can be tricky. Project Managers and HSI Leads should consider the following guidelines:

General Guidelines for Trade Studies

- ✓ Do not let technology needs overshadow human aspects.
- ✓ Be explicit regarding the consequences—monetary and life cycle—of planned trade-offs so good decisions can be made.
- ✓ Work with the user on all trade-off decisions.
- ✓ Ensure trade-off decisions do not compromise mission success.

3.5.1 Identifying Human-Centered Trade-offs

HSI uses a variety of analysis methods to evaluate systems with respect to the six key domains. A critical part of the "I" in HSI is the analysis in which system features and attributes are "traded off" to satisfy constraints on system LCC, performance, and development/delivery schedule.

The primary goal when conducting proactive trade-off analyses among HSI domains and across the system is to ensure the system meets or exceeds the performance requirements. HSI emphasizes the importance of considering interactions and trade-offs across the HSI domains during the requirements identification and technology development process. Similarly, automation level and technology complexity may impose additional requirements on human performance characteristics (e.g., level of education required) and training needs for operating, maintaining, and/or supporting systems. These trade-offs need to be explicitly considered early in the technology procurement and development process to ensure effective performance and minimize total system LCC.

Identifying trade-offs represents a unique challenge to articulate and assess human-centered perspectives. Gaining a deeper understanding and more insights into human-centered design will require designers of socio-technical environments to explore additional objectives and take the findings of different research disciplines into account.

Instituting HSI requirements in system development and acquisition programs leads to the inclusion of human-centered considerations in trade studies and trade-off evaluations. A variety of measures can be employed to set up an effective trade that directly or indirectly affects cost. But other equally valuable criteria can be established according to project goals that are not cost-based, but values-based.

The perceived benefit of HSI to a project depends on the priorities of its stakeholders. If the stakeholders place a high value on a design that reduces operational costs and optimizes human efficiency, then the engineering team can establish criteria to drive the trade space. Reducing cost, in and of itself, is not always the top priority, but must be considered along with other selected criteria. The criteria will be tailored to the needs of the individual project trade-off, which can be performed at a system, element, unit, or component level as needed.

The primary purpose of this section is to encourage a wider range of criteria when setting up the trade study or trade-off matrix. A few examples are provided in Tables 3.5-1 and 3.5-2.

Table 3.5-1. Example HSI Trade Study Evaluation Criteria

Trade Study	Example Evaluation Criteria
Crew-operated Instrument or Medical Device (multiple sources)	• Portability: attach points, handles, size, cabling • Power: battery management logistics, cabling, heat, noise (fans), interface availability and type • Calibration: crew time, periodicity, complexity, accuracy • Complexity to operate (subjective assessment) • Display readability
Net Habitable Volume (multiple designs)	• Proposed crew size > consumables, life support, etc. • Proposed design reference mission (DRM) timeline • Vehicle size constraints
Display Interface Design	• Display hardware: quality, size, resolution, reliability, maintainability, placement affordances and constraints • Cost • Usability quality components: intuitiveness, learnability, effectiveness, task efficiency, memorability, error tolerance (user errors, error recoverability); user engagement and satisfaction • Readability: adverse conditions (vibration, turbulence); lighting conditions; visual angles, viewing distances • Anthropometrics: reach and accessibility • Controls: input sensitivity and accuracy (e.g., touchscreen, rotary controls, push buttons); ease of operation, feedback
F119 Engine (Pratt & Whitney)	• Increased engine reliability • Personnel and time reduction for maintainability • Increased safety, supportability, operability, and stability • Reduced training time and/or increased training effectiveness
Ship Command Center Simulation for Ship Layout	• Cost and availability of hardware/software • Schedule (ship construction) • Accuracy of analysis • Safety and human performance
Vehicle Collision Avoidance Automated System (CAAS)	• Increased safety • Maintain driver-in-the-loop (normal attentive vehicle control) • Intuitive user interface • Accuracy of automated system (e.g., driving state sensors, time to trajectory/lane crossing estimates, false alarm probability, CAAS actions) • System cost and reliability

Table 3.5-2. HSI Trade-Off Examples

Example Topic	Trade-Off	Considerations (HSI)
Handheld Device	Portability: attached power cable vs. replaceable batteries	• Battery Logistics cost • Time impact for replacing batteries • Battery run time
Line/Orbital Replacement Unit (LRU/ORU)	Testability: built-in diagnostic self-test vs. operational test; redundancy vs. ready spare on-orbit	• Mass, power, complexity, communications for added capability • MTBF; R&R periodicity • MTTR; R&R on-orbit time • Criticality of function
Emergency Egress and Post-landing Survival in Sea States	Cabin temperature vs. acoustic noise vs. suit and vehicle design vs. crew health and performance	• Vehicle constraints: battery life, communications, life support • Landing ConOps • Human health constraints
Water Sampling Device Complexity	Crew time vs. cost of automated or autonomous system	• Design cost • Crew time impact for repetitious operation • Design for back-up manual mode
Two-story Ship Command Center	Structural integrity and constructability vs. human performance	• Decreased structural integrity • Cost, schedule, and construction feasibility • Increased situational awareness • Increased communication and execution • Task execution response time
Personnel Resource Requirements (e.g., flight and space vehicle crews, control room operators, maintainers)	Reduction in number of required personnel vs. human performance	• Workload: fixed amount of work (maintenance tasks); reduced crew = increased workload • Habitability: reduced crew = longer work hours resulting in cumulative fatigue • Safety: fatigue = increased mistakes, errors of omission, equipment damage • Survivability: reduced crew = fewer people available to respond during emergency or off-nominal situations, resulting in a threat to personnel and systems

For decision-making, establishing an exact cost is less important than a measurable metric that translates to cost consequence. In this approach, the true cost is not actually calculated, but a metric is derived instead. The cost-equivalent metric is used in evaluations or even requirements to produce desired outcomes in decision-making and design options.

Another prime consideration for decision-making is larger architecture-level trade-offs, which can have a significant impact on LCC. These decisions must be made early in the project life cycle and validated with the other project stakeholder values, goals, and objectives. The range of choices is extensive, but can include “moving the sliders” for such things as:

- Function allocation to hardware, software, and humans
- Autonomy
- Automation
- Redundancy, fault management architecture
- Engineering development tool choice (model-based, etc.)

- Risk tolerance for new technologies
- Operational environments and envelopes

The review of human-centered trade-offs also occurs at the programmatic level and with high-level architecture decisions. From a programmatic perspective, there is often a need to consider the level of involvement of human interaction with the different aspects and components of the system (falling in the realm of function allocation) as well as the concepts of operations and flight rules associated with those interactions. The NASA Risk-Informed Decision Making Handbook (NASA/SP-2010-576) provides a reference that many programs consult when making these decisions. Some specific examples of human-centered trades include the level of personnel interaction time during specific mission phases (how much engagement is desired and needed vs. what would be deemed excessive, particularly for activities such as maintenance and cleaning or trash management; the number of operators/maintainers required for each task (a measure of resource demands and allocation); ease of operation (does a design trade make performing a given task harder or easier?); ease of access (does a design trade increase human ability to interface with a system, or make it harder?); ease of repair (impacts on repair time demands, tool needs, parts usage, and logistical impacts); amount of training required (specialized expertise vs. general skills and knowledge); and ease of disposal. Table 3.5-3 provides additional examples from each of the HSI domains.

LCC and trade studies are just two examples of HSI measures used in project designs. An additional discussion on HSI metrics can be found in Section 5.2.2.8, Developing and Using HSI Metrics.

Table 3.5-3. Examples of Program, Architecture, and Design Decision-Making Criteria

Criteria	Domain	Criteria Type	Units of Measure
Does the performance of a task involve handling of hazardous materials? If so, what types of controls or personal protective equipment must be added to the system design?	Safety	Binary	Affirmative or Negative, with Mitigation Steps
What is the mean time to "turn around" a system for next mission or test? Does it meet the time constraints and resource allocations of the design reference mission and future system plans?	Maintainability and Supportability	Duration	Time (Hours, Days, Months)
What are the levels of acoustic noise generated by system or present in the working environment?	Habitability and Environment	Time Weighted Average	Sound Pressure Level (SPL), measured in dB(A)
What are the cognitive demands of the task and the associated workload levels?	Human Factors Engineering	Threshold (Maximum)	Workload Score (NASA TLX or Bedford)
What number of task steps are required to execute a given activity? This is an industrial engineering measure of efficiency.	Operations	Frequency Count	Task Steps
What is the amount of training required to master a task (including trainer and trainee time)?	Training	Duration	Person-Hours

Example: Control Room Design and Training Trade-off

When designing a complete system (e.g., space vehicle, aircraft, control center), the training required for users becomes an attribute of the system with a quantifiable LCC. This cost can be evaluated and traded with other attributes/costs. For example, if a control room display is configured with little regard for its ease of use and depends heavily on humans' capabilities to integrate information and carry out complex system tasks, there will almost certainly be a heavy training requirement. The costs related to developing performance supports (job aids, resident training, simulators) may also be high. Alternatively, the same system might be configured to automate complex tasks, allocating them to technology rather than humans to reduce demands on operators. This requires additional technology integration, software programming, and other up-front costs.

The following example from the International Space Station (ISS) is provided for additional emphasis:

Example: Emergency Lighting

During ISS development, a requirement for emergency lighting was established, intended to provide module exit pathway illumination during a power outage. The original fielded solution, Emergency Egress Lighting System (EELS), failed to take into account the extensive crew time required to change the batteries that kept the system operational. There were also extensive logistics for flying up batteries. After many "lost" crew hours, a second design iteration produced a more elegant, low-cost and low-impact solution: circular photoluminescent (glow-in-the-dark) markers, known as the Emergency Egress Guidance System (EEGS).

In this example, crew work-hours were used as a cost-equivalent measure. The potential solutions in the second, experience-informed, iteration considered the monetary cost of the battery logistics as well. All potential design solutions were compared, using both the cost-equivalent crew work-hours and the actual cost logistics metric. The selected solution was low-cost for both metrics.

It should be noted that this example for ISS and emergency lighting is a good example of a metric used to make design decisions and improve the HSI aspects of the system. However, it should also be noted that this solution in the long term (the use of luminescent decals) was found to be suboptimal, as the decals often did not receive enough light to fully charge, resulting in them being dimmer than needed. Current programs (e.g., HLS and Gateway) have adopted different lighting requirements that stipulate different solutions. However, this is a good example of the maturation of solution sets over time based upon both metrics and operational inputs—key aspects of HSI.

4.0 Agency Advisory HSI Resources

4.1. Community of Practice (CoP)

The NASA HSI Community of Practice is an Agency-wide forum jointly chartered by the Office of the Chief Engineer (OCE), Office of the Chief Health and Medical Officer (OCHMO), and Office of Safety and Mission Assurance (OSMA). All three offices agree that HSI practices play an integral role in NASA's processes to provide efficient, effective, and safe outcomes for programs and projects, improving mission performance and safety and providing increased mission return. The HSI CoP has been established to bring domain subject matter experts from the three governing offices, the Centers, and Mission Directorates together to promote awareness and inclusion of HSI within the Agency.

The main CoP functions are to:

- Share HSI expertise, lessons learned, and best practices of all HSI domains,
- Help promote HSI advocacy by communicating the benefits of HSI to Program/Project Managers, Systems Engineers, and stakeholders,
- Help improve and advance the existing practice of HSI based on Agency policy and guidance.

The CoP is an advisory group to the three offices and advocates for HSI practices and expertise to be fully integrated into program/project life cycles of NASA's missions. The CoP serves as an Agency resource to build relationships internal and external to the Agency regarding HSI practice and facilitate the inclusion and advancement of HSI by promoting the benefit of emphasizing the role of humans during systems development and operations planning. This Agency resource can enable HSI incorporation into the Agency's portfolio and serve as a valuable resource in the planning, managing, and implementing of HSI across the Agency.

4.2 Technical Authority

The TA process is an important part of NASA's Governance that employs checks and balances among key organizations to ensure that decisions have the benefit of different points of view and are not made in isolation [ref. 22]. NASA separates programmatic and technical roles to provide an organizational structure that emphasizes the TAs' shared goal of mission success while taking advantage of the different perspectives each brings. Procedurally, HSI is unique to NASA in that it is a systems approach that spans all three TAs, as shown in Figure 4.1-1 [ref. 23].

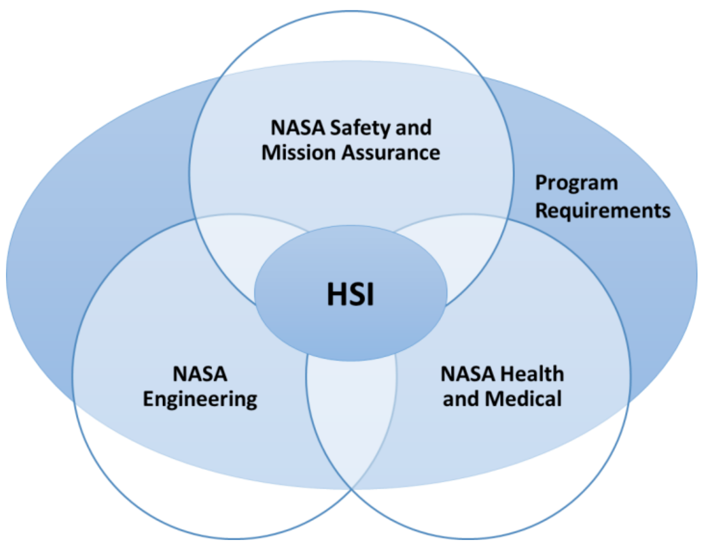

Figure 4.1-1. Technical Authority Elements

The HSI Lead should recognize that while working within the project, the HSI team is also closely associated with technical authority stakeholders. For example, the SMA TA and ETA provide standards applicable to all Agency programs and projects, while the Health and Medical Technical Authority (HMTA) promulgates human system standards at the Agency level (NASA-STD- 3001) that are specifically applicable to human spaceflight programs and projects. The HSI effort creates one of the balance points between institutional standards and programmatic goals, as illustrated by the following example.

Example: HSI in Practice—Constellation Lessons Learned

NASA's Constellation Program (CxP) provided a unique HSI test bed as a fundamental element of the SE process. Constellation was the first major program to have HSI mandated by NASA's Human Rating document. The CxP Human Systems Integration Group (HSIG) was part of the Systems Engineering & Integration (SE&I) organization within the Program office, existing alongside similar groups, such as Flight Performance; Environments & Constraints; and Integrated Loads, Structures and Mechanisms. This was a first for a major NASA program like the CxP. A key lesson learned was that although the HSIG successfully managed an HSI technical forum to facilitate integration and issue resolution, and involvement of and coordination with NASA technical authorities was leveraged to ensure successful development of a human-rated system design, the program structure itself did not provide the necessary top-down authority to drive integrated design, which hindered the HSIG's impact. This is a key lesson learned for future programs: not only does HSI need to be implemented, but HSI personnel need responsibility with commensurate authority (perhaps through elevation to a higher control board) to successfully perform their duties.

Case Studies Highlighting Management Commitment to HSI

D.1 Inadequate Consideration of Operations During Design: Shuttle Ground Processing

D.6 Effective Culture, Requirements and Trade Studies: The Reliable and Maintainable F-119 Engine

5.0 Implementing HSI

As of 2021, NPR 7123.1 and NPR 7120.5 require NASA technical efforts to implement HSI processes and practices throughout the project's life cycle to positively influence total system effectiveness and LCC. Ultimately, the project manager is responsible for the planning, implementation, and documentation of HSI processes, obtaining an HSI Project Lead and ensuring that HSI is integrated into the SE process throughout the project life cycle. To successfully implement HSI, the development and execution of a comprehensive HSI Plan and formation of an HSI Team or Working Group are essential.

5.1 Collaboration

For the HSI Lead, collaboration with the PM, Systems and Chief Engineers, other project leads, and the overall program management and SE infrastructure is the most appropriate and efficient means of ensuring HSI is a core part of every project. The goal of working within an agreed-upon structure is to enable project stakeholders and experts from varied disciplines to consider and address relevant issues and challenges of shared concern and resolve design trades in a rational and cooperative environment. The purpose of working collaboratively is to create an ideal, shared vision that all stakeholders can agree upon, commit to, and finally create and implement action plans.

It is essential for the HSI Lead to collaborate with many aspects of the project, as well as with relevant institutional organizations where HSI domain SMEs are likely located. HSI is inherently part of the larger project's Systems Engineering and Integration (SE&I) infrastructure and has a natural collaborative role with system engineers in defining the project's mission and in designing and integrating the total system (human + hardware + software + environment) needed to accomplish the mission in the intended environment. Conceptual design, architectural formulation, function allocation, and operations development are all desired processes and outcomes of early collaboration. HSI collaboration continues through all project phases, using NASA SE processes outlined in NPR 7123.1 and the SEHB. Figure 5.1-1 depicts many of the notional HSI external interactions.

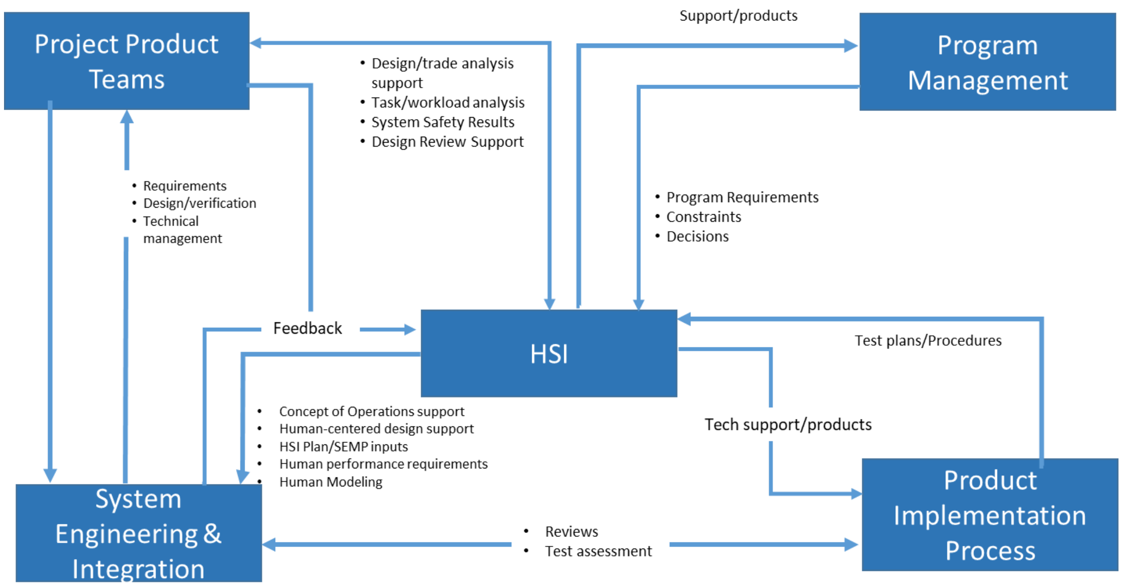

Figure 5.1-1. Notional HSI External Interactions

5.1.1 HSI Team Collaboration

The establishment of an HSI Team is recommended practice to efficiently and effectively implement HSI domains across a project's various disciplines. The HSI Lead should assess the types of human system design expertise needed and form a team appropriately composed and organized to fulfill the HSI plans, activities, and products necessary for the particular project. Valuable resources in establishing the HSI team and identifying domain and other SMEs are found within the Agency HSI CoP (each NASA Center has core members in this community) and the TA representatives at each Center. Team composition is determined by project scope, nature of the system and operational mission, and the types of human system design challenges anticipated.

HSI Teams can be either formal or informal, depending on the size and scope of a project. However the team is structured, funding must be provided by the project to ensure the proper products (including specification content) are developed. At a minimum, this means part-time funding for the HSI Lead and domain SMEs.

A formal HSI team is structured with dedicated domain team members funded by the project and included in the project's organizational chart. A formal HSI team may also include additional HSI practitioners and representatives from the intended user community based on program or project needs and the level of HSI effort determined (See Section 5.2.1 for additional information).

An informal HSI team includes domain SMEs that are called upon for temporary input to meet a project goal. Together, the HSI Lead and Project Management plan and negotiate the necessary institutional SME resources as early as practical for the HSI team to form and create an implementation plan prior to early-phase activities, such as requirements definition, system architecture development, and functional decomposition. The HSI Lead should know the SE and programmatic methods required to integrate human performance and capacities into the project's mission and resulting systems design, development, and implementation. When project resources are constrained, or the scope of the project is small and there is not an officially recognized HSI team of domain SMEs, it will be incumbent upon the HSI Lead to informally, yet fully, use resources across the Agency to optimally implement HSI.

Consideration of SMEs is a critical part of the early definition (e.g., Concept of Operations (ConOps)) and design process (e.g., requirements and analyses). Table 2.2-1 lists the domain areas for HSI that will provide the needed skill base and examples of specific HSI expertise available from the domain SMEs. As Figure 2.2-2 illustrates, each HSI domain has the potential to affect and interact with the others, making an integrated discipline approach critical to the success of the overall effort. The HSI Lead holds the key to leveraging their knowledge and skills through integration across HSI domains as well as established and team-specific SE techniques.

For successful HSI implementation, the HSI Team should include or have access to sufficient depth and breadth of HSI domain discipline technical expertise to implement an HSI Plan and to meet HSI objectives. The HSI Team executes the tasks required for HSI integration across the HSI domains and NASA organizational structures, manages HSI documentation, coordinates with SE, technical disciplines, and SMEs, and provides technical expertise and recommendations. Within the HSI team, extensive interdisciplinary collaboration is required. For all the other described roles of an HSI Team, it is critical to ensure that there is integration outside of the HSI Team and primary NASA organizations responsible for HSI. This is accomplished through identifying appropriate points of contact; proactively ensuring the HSI Team is included as stakeholders for requirements and processes owned by other teams; establishing rapport with teams across NASA organizations and HSI domains; educating the project about the role of the team; and communicating regularly and clearly. Activities that must be integrated across domains and organizations include requirements and verification work, risk assessments, and developmental testing and trade studies.

The SMEs' efforts include development of HSI requirements for the program or project, application of those requirements to the system, and involvement in verification of the system as meeting the requirements. Depending on the nature of the project, the SMEs also may engage in product development, evaluation, and validation efforts, including planning and execution of integrated system tests, demonstrations, analyses, and ultimately, system operations. The HSI Lead manages the team's integration efforts to lend appropriate, balanced weight to all SME inputs without neglecting those that may be specialized or that are more difficult to incorporate into design or operational methods, as illustrated in the following examples:

Subject Matter Expertise Collaboration Example:
Collaboration Across Disciplines

Knowledge about human deconditioning after extended exposure to weightlessness is specialized and is the subject of multiple lines of research to improve the scientific and medical evidence base. Knowledge in this area is continually improving, and SMEs are the primary source of the most current insights.

An HSI Lead may actively consult with SMEs in the Sensorimotor, Musculoskeletal, Cardiovascular, and HFE areas to provide a comprehensive, integrated view of deconditioning as a design influence on crew tasking at the time of spacecraft landing. This would provide the HSI Lead with implications for the vehicle's design, to ensure crew health and safety risk was mitigated to the appropriate level to meet NASA human system standards.

Subject Matter Expertise Collaboration Example:
HSI-Safety-Operations-User community (Compressor Station Upgrade Project)

The HSI framework includes safety considerations across all NASA technical efforts where humans are an integral component of the system, including NASA facilities projects, such as the major upgrade of an Air Compressor Station.

An HSI Lead may consult with facility, safety, training, and operations SMEs to provide an HSI assessment of the design, installation, and operation of the system to ensure operator safety, risk reduction and mitigation, and optimized system performance. A compressor station is a complex system which requires operators to operate, monitor, service, and maintain the system in a challenging environment. The HSI practitioner can ensure that the human component is considered prior to the new installation of the compressor system so that safety issues can be eliminated or mitigated via system/installation design enabling operators to safely conduct system operations, service and maintenance tasks.

5.1.2 Project Technical Team, Working Group, and Board Participation

In the performance of their role, HSI Leads coordinate with the other engineering teams and within the HSI domains, ensuring that system requirements are flowed down, specialists are appropriately involved in design decisions, trade-offs are made analytically, and the integrated system fully considers the human components. Programs and Projects will typically establish one or more forums to assist in the integration, collaboration, and control of their technical efforts. Many of these established teams, groups, and boards will cover topics that relate to HSI. These forums may or may not be chaired by HSI Team members, but HSI Team members must participate. NPR 8705.2 requires the program to establish an HSI team to support the implementation of the HSIP. NASA-STD-3001 extends human considerations in NPR 7123.1 and NPR 8705.2 to include a detailed crew task analysis and HSI team and control board.

Some additional examples are identified as follows:

- HSI Working Group/Integrated Product Team (IPT)
- Risk Management Board
- Requirements and Verification Board
- Modeling and Simulation/Model Based Systems Engineering (MBSE) Management Board
- Certification/Airworthiness Working Group
- Systems Engineering Working Group, Control Board, etc.
- System Safety Working Group
- Integration & Test Working Group
- Flight Test Operations Working Group
- Cockpit Working Group
- Air Vehicle IPT
- Performance and Simulation IPT
- Test and Evaluation IPT
- Logistics IPT
- Software IPT
- Crew Systems IPT
- Production IPT

Case Study Highlighting Team Collaboration

D.1 Inadequate Consideration of Operations during Design: Shuttle Ground Processing

5.2 HSI Planning and Execution

HSI planning begins at the earliest outset of a project, before Pre-Phase A, so that the HSI team is fully engaged through Pre-Phase A. In addition to learning about the goals and intent of the project, the HSI Lead should begin focusing on putting in place the people, plans, processes, metrics, and products that will yield life-cycle benefits to the particular program or project and begin the documentation of these within an HSIP. HSIPs are required for the Agency efforts as defined by 7120.5: Projects, Single-Project Programs, and Tightly-Coupled Programs.

The purpose of the HSIP is to document and plan the scope of HSI for the effort (be it a reduced scale for a small project, or alternatively a comprehensive HSI implementation for a major program), identify the steps and metrics used throughout the project's life cycle, identify the HSI domains engaged in the effort, and document the HSI methodologies and approaches to be taken to ensure effective HSI implementation. This handbook provides guidance on planning and implementing HSI activities for these Projects and Programs and provides a comprehensive, yet tailorable, template for an HSIP.

HSI planning integrates across all HSI domains and with the SE processes to have significant impact on project performance, LCC, and schedule. The systems engineer may be skilled in the art and science of balancing organizational and technical interactions in complex systems but may not have experience in human-centered design or in HSI domain disciplines. Gathering the appropriate human-centered discipline SMEs and HSI domain SME's is essential for project success. The HSI Lead must communicate effectively with the project team to generate the necessary level of HSI engagement. To support that outcome, this section provides an in-depth look at skills and management approaches needed to promote successful HSI processes and products.

The following figures are examples of notional organizational structures of different types of NASA program/projects depicting how the HSI Lead and HSI Team could be integrated within each structure. The organizational structure may vary based on mission type, organizational needs, and Program/Project culture. Based on these and other factors, the HSI Lead and project management will determine the best placement for the HSI function during Pre-Phase A.

Figure 5.2-1 shows a notional organizational structure for projects or single-project programs, where the HSI function is best placed within the Systems Engineering (SE) component of the project, working directly with the SE Lead and SE&I Team. Figure 5.2-2 provides a notional example of placement of HSI within tightly-coupled programs where there is a need for an HSI function at the program management level providing insight/oversight and coordination of all HSI activities and issues that affect the interfaces between projects.

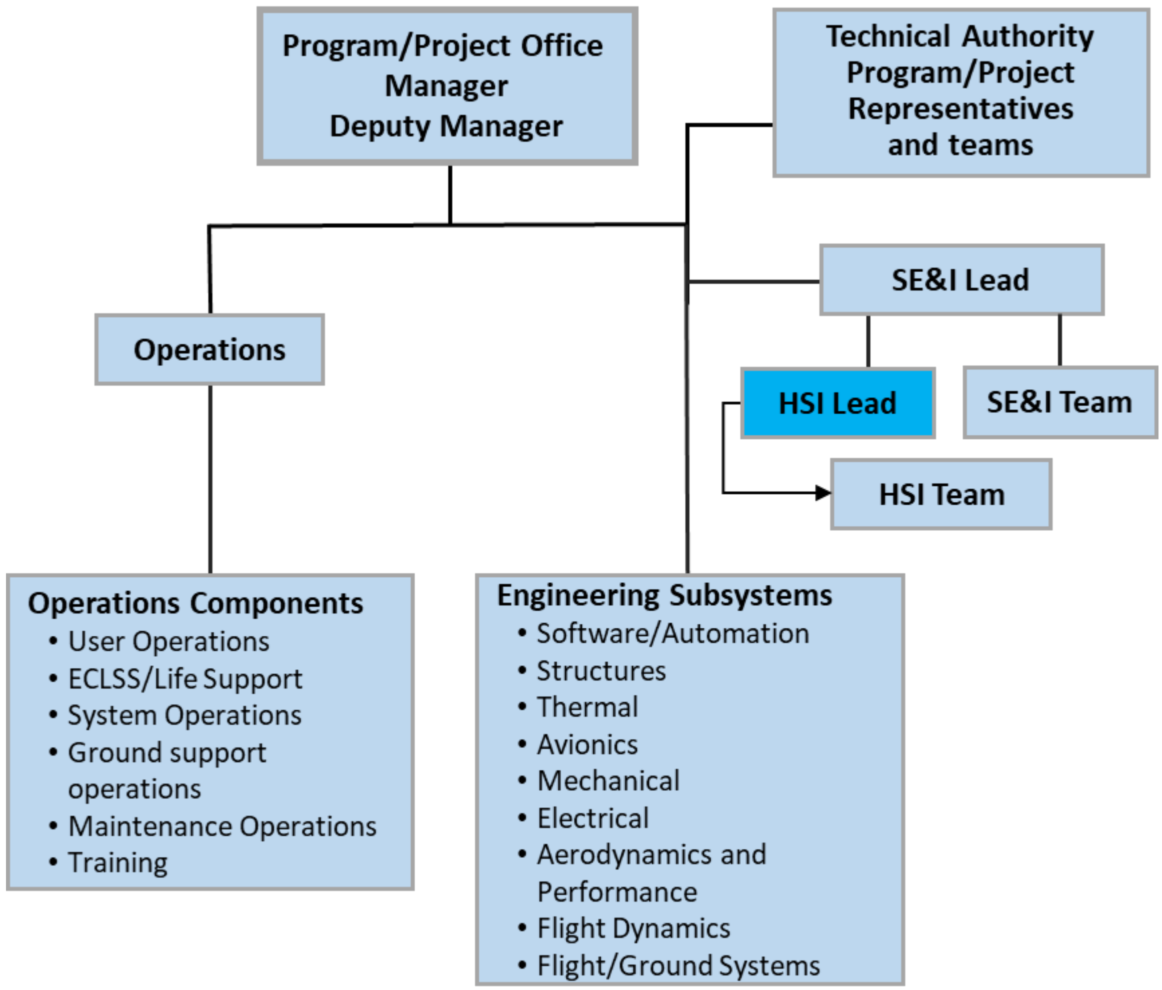

Figure 5.2-1. Notional Project or Single-Project Program Organization with HSI

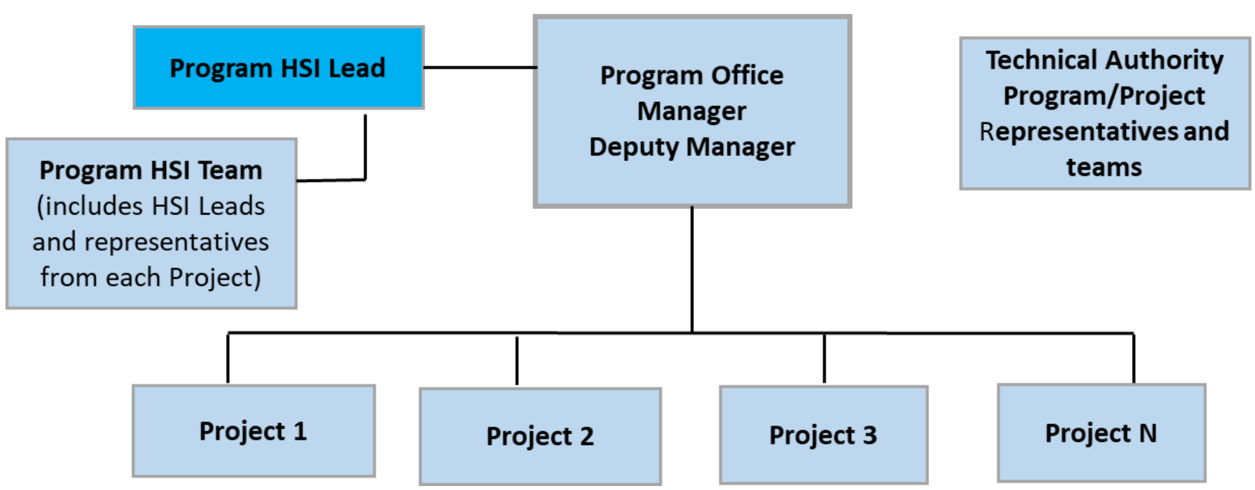

Figure 5.2-2. Tightly-Coupled Program Organization with HSI

5.2.1 Scaling and Tailoring HSI

NASA recognizes the need to accommodate the unique aspects of each program/project to achieve mission success in an efficient and economical manner by tailoring the overall technical efforts as appropriate. Tailoring is the process used to accomplish this and is defined by NPR 7123.1 as "the process used to adjust or seek relief from SE NPR requirements consistent with program or project objectives, allowable risk, and constraints."

Just as the overall technical and management efforts are tailored for a particular project's need, the HSI effort required of a project should be similarly scaled and tailored to fit a project's size, budget, mission, and scope but should define the approach for the integration of human performance characteristics into the system design (to include operators, maintainers, and support personnel, as applicable). An HSI Lead should assist program/project managers with determining the level of HSI effort required for each program/project as shown in Table 5.2-1. The HSI Lead is cautioned against using the project budget as a primary consideration when determining HSI effort.

HSI requires participation of highly qualified personnel who understand how to integrate human performance and capacities into research, design, development, and system implementation. HSI represents the human in all system design, analysis, and planning activities and the role requires knowledge of human capabilities that others in the program lack. For projects that require large-scale HSI efforts, extensive institutional resources may be dedicated to HSI. A comprehensive, knowledgeable HSI team is essential to mission success. For small-scale HSI efforts, identifying the scope is critical, since the smaller HSI team size will require precise planning of a resource-constrained SME skill set. Understanding the domain expertise required for a project allows the lead to sharply focus available resources on the most critical HSI efforts documented in the HSIP (see Section 5.2.2.6 and Appendix A for additional information). The project or program manager should enlist the full assistance of an HSI Lead to scope the HSI effort, create an HSIP, form an HSI team, and advocate for effective HSI implementation throughout the project life cycle.

For small-scale projects, which may lack an assigned human factors engineer or a team to support an HSI Lead, it may be best to find someone with a strong HFE background who has been trained in HSI and SE to serve as the HSI Lead. HFE is a critical domain for HSI, responsible for characterizing human performance characteristics and applying knowledge of these to hardware/software engineering systems design. An HSI Lead in these projects should have, at a minimum, informal reach-back capability to other domain experts to assist as needed for expert consultation. When project resources are constrained or the scope of the project is small, it will be incumbent upon the HSI Lead to informally, yet fully, utilize resources across the Agency to optimally implement HSI within a given project to assemble an informal HSI Team.

For medium-scale projects with a team of experts assigned across the HSI domains, the HSI Lead assigned should have HSI education and experience to understand the broad requirements and scope of HSI and each domain, in order to integrate across them. For medium-scale projects not supported by HSI domain subject matter expertise, it would be best to follow the qualifications described above for small-scale projects.

For large-scale projects, an HSI Lead with both HSI experience and HSI training is preferred, like medium-scale projects above. Large projects are expected to have an HSI Lead supported by a team with at least one HSI practitioner plus individual expertise represented across all HSI domains. For projects that indicate large-scale HSI efforts, significant institutional resources may be dedicated to HSI.

HSI approaches can also be applied to individual end items (e.g., exercise equipment, tools) using the guidance in this section. Projects will often produce a system that contains lower-level components, units, or elements that are less human-oriented and so may be treated with less attention to HSI techniques. For example, a structural component not directly exposed to human interaction may have very few HSI requirements that drive its design. For items such as these; human interaction is the key. The effort may be highly constrained for limited resources when scaled to this level, but the HSI key concepts still apply: “human considerations” are fundamental to HSI, no matter how big (or small) the project. A simplified, notional list of project characteristics is shown in Table 5.2-1, which can be used by the Project Manager or the HSI Lead to scale the HSI effort along the lines of the example roles and products shown in Table 5.2-2. These tables and their illustrated characteristics are intended as useful indicators, not requirements. It is not essential that all the characteristics for project size be met to assign an overall size category. Generally, the HSI effort for a project should be sized and focused based on its most critical safety or human involvement characteristic(s).

Table 5.2-1. Project Characteristics Relevant to Scale of HSI Effort

Level of HSI Effort	Human Safety	Human Involvement
Large-Scale HSI Effort	• Typically Cat I/II or Class A/B Programs and Projects • Highly complex systems • Monitored/operated by humans • Significant potential risk to humans, equipment, and/or facilities • Hazards controls needed • Human-rated space programs • Aeronautics programs requiring airworthiness certification • Human-operated aeronautics programs • Human-managed robotic programs • Life-sustaining equipment • Potential loss of life or mission risks managed	• Large, complex hardware/software systems • Tight coupling of human actions to critical system performance • Extensive training required • Humans are involved routinely in logistics or maintenance operations • For systems with human operators (space, aero, robotics) • Humans involved with day-to-day operations (e.g., astronaut crew or pilots, robotic operators, etc.) • Ground crew or operators closely monitoring the system and intervening to resolve issues • System or product requires significant human involvement to maintain or assemble
Medium-Scale HSI Effort	• Typically Cat II/III, Class B/C Programs and Projects • Modest risks and hazards • Hazard controls may be needed • May support human-rated programs, human operated aeronautics programs, or human-managed robotic programs	• Medium system complexity with a number of hardware/software subsystems • Moderate coupling of human actions to critical system performance • Human operators essential to mission success, humans work with, control or monitor the product • System or product requires significant human involvement to maintain or assemble • Some automation • Training required

Level of HSI Effort	Human Safety	Human Involvement
Small-Scale HSI Effort	• Typically Cat III, Class C/D, or Class D/E (software) projects • Low-risk hazards	• Simple systems with small number of hardware/software components • Loose coupling of human actions to critical system performance • Infrequent human interaction in operations • Humans involved with some aspects of the system, humans use the product • Automation used to reduce human interactions • Some training required

Table 5.2-2. HSI Tailoring

HSI Role or Product	Large-Scale HSI Effort	Medium-Scale HSI Effort	Small-Scale HSI Effort
HSI Lead	Necessary	Necessary	Necessary
HSI Team	Necessary; formal project team preferred, including one or more HSI practitioners and representatives from user community	Recommended; blend of formal and informal team preferred, may include additional HSI practitioner(s) and representatives from the user community, given program/ project needs	As-needed; informal team
HSIP	Standalone Doc	Standalone Doc	Standalone Doc
ConOps Development	Co-Lead/Significant Contributor	Contributor	Contributor
HSI Requirements	Standalone Doc or Part of Project Docs	Part of Project Docs	Part of Project Docs
Lessons Learned Capture	Expected	Support Process	Desired
Mission Architecture Development	Significant Contributor	Contributor	As needed

One may look at a Large Scale Space Telescope Project, like the James Webb Space Telescope, and think that HSI is not needed at all and then question looking at the column entitled “Human Safety” in Table 5.2-1, where from a cost standpoint, it would lead one to believe that a Large-Scale HSI effort would be recommended. As has been stated previously, the HSI Lead and Project Management should not base HSI efforts on cost metrics alone; however, serious consideration of the potential value of HSI inclusion should be made. This particular project experienced several cost overruns, schedule delays, and challenges in the integration and test phase of the life cycle. In 2018, NASA included the following among its findings and recommendations to the Webb Independent Review Board [ref. 24]:

- Human mistakes were made during Integration and Test and the board recommended corrective actions for processes, training, personnel certification, individual accountability, and a robust testing, analysis and inspection process.

- The Project should review all simulators/testbeds and required usage against prelaunch tests and rehearsals, post-launch deployment anomaly resolution, fault isolation and correction.
- The GSFC JWST Project Office should develop a staffing plan that meets the needs of I&T and operational readiness.

While the inclusion of an HSI Lead and HSI team may not have solved all of the challenges encountered or prevented all of the mistakes made, there is a strong potential that JWST would have benefitted from having an HSI Lead working to integrate across the HSI domains. From the above Webb Independent Review Board findings, the HSI domains of Training and Operations are called out explicitly. Safety in the form of quality assurance is included in the inspection process mentioned above as well. Human Factors Engineering would also be essential for many of these areas. In hindsight, an HSI Lead performing a task analyses for the I&T effort of the project may have provided project management a better understanding earlier in the life cycle of what would be needed and the risks to human performance and mission success. Therefore, looking at this from a different perspective than assuming that HSI is only needed if there is a distinct human operator interface, would lead to a recommendation in this case of perhaps a Large Scale HSI effort, where the driving factors for this would be in the Human Involvement column—"Large and complex hardware/software systems" and "System or product requires significant human involvement to maintain or assemble."

Figure 5.2-1. Work Under Way on the James Webb Space Telescope *(Photo: NASA.gov)*

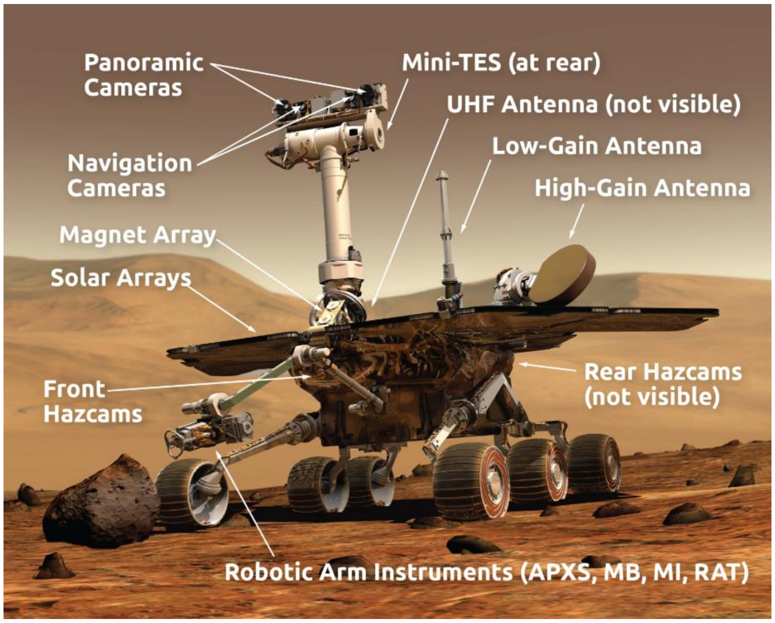

Figure 5.2-2. System Components of the Mars Exploration Rover, left, and the Rover in the Clean Room, above *(Photos: NASA.gov)*

Similar to the JWST example, there are examples of failure to sufficiently apply HSI in the design of the Spirit and Opportunity Mars Exploration Rovers (MER). The following example contains another, less obvious, example of what perhaps should have been a medium- to large-scale HSI effort. HFE analyses, combined with function allocation focused around the accessibility for maintainability and supportability and the operations required, would have mitigated the design concerns mentioned below for the test battery.

Peter Illsley, a mechanical engineer for these rovers at JPL, provides the following lesson learned: [ref. 25]

> *"Early on in the design of the internal packaging of the MER Rover systems, we made a decision to treat the rover body as a box and install the Rover Electronics Module from the top and then close the box with the Rover's structural lid on top which held the solar arrays, the communications antennae, and science camera mast. Further, we had located the Rover's battery in the bottom of the body, underneath the electronics module to help the center of mass a little bit lower to the surface. The processes for installing all of that equipment were lengthy and very risky, with damage to hardware always a concern and a constant threat to the immovable launch date. I personally lost many nights of sleep every time I knew we were either installing or removing that hardware from the Rover.*
>
> *In the course of the build and test of the Rover, the test battery had to be swapped out for the one intended for flight. To get to it, we had to remove the equipment deck and the electronics module in several shifts of harrowing work only to take out the battery and put in a new one. Had we decided in the design phase to question our earlier assumptions about the battery location, we could have cut down the number of highly-risky operations and saved a lot of time and stress-driven gray hairs."*

With NASA CubeSat projects, the focus is on designing for simplicity. However, these projects can include complicated designs (tri-folded wings, expensive payloads, directional antennas, bus and payload, etc.) that are more challenging where resources don't always match the CubeSat paradigm of rapid and cheap. Additionally, these projects do not perform the full set of subsystem-level testing which means that issues may not be discovered until the satellite is completely assembled. Therefore, the designs of such systems must account for the potential need for disassembly, re-work, and reassembly that can prove difficult for human maintainers and assemblers due to the size of these components. This is an example of where a small-scale HSI effort may be warranted with a part-time HSI Lead, an informal HSI team, and a tailored minimal HSIP, if required [ref. 26].

5.2.2 HSI Approach Execution

Implementation of an HSI approach requires development of various products, which guide the execution of the approach. Key skills to effectively implement HSI are integration of subject matter expertise and development of HSI products including those identified in Table 5.4-1. Early HSI efforts are leveraged in assessing training needs and usability. In addition, an effective approach uses metrics and lessons learned to gauge effectiveness and provide insight for future HSI implementations.

Throughout this handbook, we describe how the HSI Lead engages with the project to develop the HSI products, brings in experts for specific tasks, and supports the entire life cycle. This comprehensive approach ensures that HSI is inherent in project technical and management activities. The HSI Lead is also a key participant in reviews (e.g., CDR) to detect problems hidden in a complex design. This is accomplished by being immersively engaged with the development effort.

5.2.2.1 Developing a Concept of Operations

Per NPR 7123.1, the ConOps for a project, typically developed early in Pre-Phase A, describes the overall high-level system concept from an operational perspective and helps facilitate an understanding of system goals and mission objectives. The ConOps should describe the system in enough detail to stimulate the development of the requirements, interfaces, and architecture related to its user elements. The amount of architecture or “design solution” included in the ConOps is a matter of approach, but is generally kept minimal so as not to limit creative design solutions. It serves as the basis for subsequent definition documents and provides the foundation for long-range operational planning activities throughout the mission life cycle.

The SE typically leads the ConOps development team and uses the SE engine to develop initial concepts and define the roles of humans, hardware, and software in performing the mission objectives. However, because the ConOps is a driver for defining system requirements, the HSI Lead must be an integral part of the team. The HSI Lead should ensure that the ConOps considers all aspects of operations (nominal and off-nominal scenarios, including contingency and emergency scenarios), including the personnel required for operating, maintaining, and supplying the system as well as descriptions of all human interactions with the system during all operational phases, required skill sets and training needs. Due to the inclusive nature and wide scope of the ConOps, inputs must be collected from a range of sources and experienced SMEs. Effort should be taken to hold reviews and disposition comments from relevant team members and stakeholders.

Development of the ConOps can be used as a guide for characterizing function allocation between humans and other system components. As the mission objectives are refined and the life cycle of the project is clearly defined in the ConOps, describing the required human systems interactions is inherently part of the process.

CASE STUDY: Concept of Operations

D.5 Training, Simulation, Design and Human Error: The Virgin Galactic Spaceship Two Mishap

5.2.2.2 Function Allocation

The HSI Lead may conduct a function allocation analysis to determine the extent to which a given activity, task, function, or responsibility is to be automated or assigned to humans. Function allocation must be performed early in the development life cycle and is often conducted in conjunction with ConOps development. Function allocation is based on many factors, such as relative capabilities and limitations of humans vs. 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.

The resulting human functions will significantly influence design decisions by establishing which functions are to be performed by users and which by technology and should form a meaningful set of system tasks.

It is incumbent upon the HSI Lead to ensure that function allocation is not focused purely on hardware and software, but includes critical human functions required for a mission, e.g., assembly, ground operations, logistics, in-flight and ground maintenance, and in-flight operations. Table 5.2-3, Function Allocation Process, provides details on the process and potential specific HSI activities [ref. 27].

Table 5.2-3. Function Allocation Process

Function Allocation Process	HSI Mapping for Resilience
Successively define what the system must do at lower levels	Ensure that lower-level definitions include the human, or human-like, functions to be performed by humans and/or machines
Translate high-level performance requirements into detailed performance criteria or constraints to define how well the system must perform	Include human performance requirements and constraints (e.g., operator workload and availability) relative to mission performance
Identify and define internal and external functional interfaces	Define adaptive user interface and system feedback and control requirements to optimize workload, optimize safety, provide context, status, time, and priority
Identify functional groupings to highlight redundancies so they could be questioned	Resilient systems may include redundant functions—ensure functions are coordinated
Determine functional characteristics of existing components	Evaluate existing components in new contexts under a range of operating conditions
Perform trade studies to determine alternative functional approaches to meet requirements	Examine trade-offs with various levels of automation, and consider other HSI domains

5.2.2.3 Integrated Operations Scenarios (Specific to Human Space Flight)

An aspect of including the HSI domain of operations in ConOps development is the concept of Integrated Operations Scenarios (IOS). Originating from the Human Spaceflight mission planning domain, IOSs are developed to identify key issues and drivers on the operations system making them substantial to ConOps development. The scenarios are developed from the mission concept and architecture functions, and inform requirements development and technology development. As the design matures, IOSs are further developed and used to create flight plan products, such as overview timelines; resource lists; generic rules and constraints; and command, control, communication, and training plans for crew and ground personnel.

IOSs can cover nominal and contingency operation scenarios needed to accomplish mission objectives. In a human spaceflight mission example, the IOS can describe the sequence of functional tasks required to accomplish end to end functions from launch through transit, on-orbit operations, to safely return to Earth. IOS serve as reference for discussions during requirements development, task and risk analyses, concept of operations development, and as foundation to prepare a mission flight plan.

5.2.2.4 Task Analyses

To define the physical and cognitive tasks that must be accomplished within the system, and after the completion of function allocation analyses, task analysis activities are conducted across the systems and subsystems for all functions allocated to human users. Task analysis, performed by the HSI Lead, is a method used to break down an event into individual tasks, and to break down individual tasks into simpler components to enable the system designers and stakeholders to understand how the human component of the system interacts with the hardware and software components of the system. The focus of a task analysis is on humans and how they perform the task (whether as operators, maintainers, assemblers, etc.), rather than on the hardware and software components of the system. The analyses produce detailed definitions of tasks and subtasks a human is required to accomplish a higher-level task. These definitions will drive requirements development and will evolve as the system capabilities become better defined through the conduct of activities in the iterative human-centered design process.

5.2.2.5 Developing an HSI Strategy

The key to a successful HSI strategy is dependent on the comprehensive integration and collaboration of HSI products and processes across all HSI domains, as well as, other core acquisition and engineering processes. Additionally, HSI should include integration with the project's SE technical and management processes with the goal of positively impacting system performance and LCC. Successful integration is dependent on the development and implementation of an accurate and comprehensive HSIP. Leveraging the SE process, a successful HSI strategy will bring all the HSI domains together and apply their interdependencies into the design of the system.

Robust HSI efforts early in the project life cycle will drive HSI requirements development, provide an accurate representation of human performance, prevent redesign, and potentially increase system performance and reduce LCCs. This ensures that the system accommodates the capabilities and limitations of the humans – both at the overall system level and at the individual subsystem and component levels. Furthermore, the HSI strategy will ensure that the HSI requirements are accurately defined, verified with appropriate methodology and success criteria, and the products validated through developmental test and evaluation activities.

5.2.2.6 Writing the HSIP

The HSIP documents a systematic approach for applying HSI concepts to optimize total system performance (hardware, software, and human), operational effectiveness and suitability, survivability, safety, reliability, maintainability, and affordability. Meeting the requirement of an HSIP is something that can be tailored based on the scope and nature of the project, see Appendix A, HSIP Content Template, which provides the flexibility to tailor the plan to specific project needs. If a project involves significant HSI, user/maintainer training, or new human-centered technology, for example, then a comprehensive HSIP should be initiated that includes detail regarding the processes of managing HSI within the project as well as greater consideration of how an HSI Team will be created and used within the process, including roles and responsibilities of team members. A smaller project may be able to have a more streamlined version of an HSIP, and an HSI Team component that is perhaps just a single POC who coordinates HSI related issues within the project and works with the PM and other stakeholders to ensure HSI inclusion is sufficient and effective for mission success.

Additionally, the needs of the project based on nature of the mission and the product being designed help to dictate the content of the abbreviated plan. For example, very small projects with only minimal human engagement may have limited HSI involvement; while other plans, even for projects small in scale, may require significant information if the mission and design include high degrees of human interaction.

To manage HSI throughout the life cycle of a program, the HSIP should include a detailed approach for incorporating the human requirements into all aspects of system development, training, operation, maintenance, and support. It is important to note that hardware and software design requirements alone will not adequately address HSI implementation. Processes and operational requirements are also critical for HSI, and these may not be well-defined early in the life of a project. The plan provides an opportunity to document the approaches to cover areas that would otherwise leave gaps in the requirements space.

The process for writing the HSIP should follow the general steps below:

- Determine the appropriate approach for HSIP documentation, including approval authority, in coordination with the project lead systems engineer, chief engineer, and/or project management. Additionally, relevant technical authority representatives can be consulted.
- Work with project to establish agreement regarding HSIP approach, responsibilities, etc. prior to writing and baselining the content.
- Consider the guidance within this section regarding content; however, take particular note of any aspects of implementation of HSI for your project that require unique considerations.
- Begin fleshing out the content with knowns, documenting assumptions, and highlighting unknowns to further develop.
- Seek early inputs to the HSIP from experienced HSI practitioners, SMEs, and project SE&I personnel.

A sample HSIP outline follows. For more details, see Appendix A, HSIP Content Template.

HSIP Outline

Executive Summary
1.0 Introduction
1.1 Purpose
1.2 Scope
2.0 Relevant Documents
2.1 Applicable Documents
2.2 Reference Documents
3.0 HSI Strategy
3.1 HSI Program Roles and Responsibilities
3.2 HSI Team Organization
3.2.1 Technical Forums
4.0 HSI Domains
4.1 Human Factors Engineering
4.2 Operations
4.3 Maintainability and Supportability
4.4 Habitability and Environment
4.5 Safety
4.6 Training
5.0 HSI Implementation
5.1 HSI Project Focus Areas
5.2 HSI Issue and Risk Processing
5.3 HSI Activities and Products
6.0 Documentation of Lessons Learned

The HSIP should start with discussion of HSI's role in the project—its purpose and scope. This can be leveraged in part from the overall goals of HSI in general (ensuring designs meet the needs, capabilities, and limitation of users, as well as reducing life cycle cost by inclusion of such considerations early in the design process rather than as rework during operations) though there also may be program unique benefits that are valuable to identify. Examples of each of these sections and recommended content is further presented in Appendix A, HSIP Content Template.

Table 5.2-4 provides phase-by-phase details on producing and maturing the HSIP.

Table 5.2-4. Guidelines for HSIP Development and Refinement

Life-Cycle Phase	Guidelines
Pre-Phase A Phase A	Develop and baseline the HSIP based on the results of functional analyses and derived human-centered requirements.
Phase B	Update the HSIP to reflect results of human, hardware, and software task allocation determination, system specifications, and source selection strategies and results.
Phase C	Identify potential human-related shortfalls and failures in human-system integration. Develop and execute mitigation strategies. Update HSIP to include latest system specifications, safety analyses, risk analyses, integration strategy, analyses of training and support requirements.
Phase D	Update HSIP to address issues related to system integration with training and support strategies. After evaluation, incorporate results of evaluations regarding usability, operability, reliability, maintainability, and supportability of the system. Ensure testing is accomplished by operational users in operating conditions. Identify human-related shortfalls and failures in human-machine integration. After the Plan is updated, document lessons learned to prepare for the next iteration of design.
Phases E & F	These phases realize the execution of plans derived during the development and acquisition of the system (e.g., training plan, disposal plan, operational resources, survivability). This is another opportunity to collect data (e.g., habitability, usability, training, environment, safety, occupational health issues) and document lessons learned.

The HSIP will define and emphasize the HSI approach in each domain. By identifying areas of SME need, the HSIP captures rationale to size SME engagement and expertise to provide system optimization insight tailored to specific project needs. It is particularly important for the HSIP to capture an understanding of roles and responsibilities, not only within the HSI team, but also for the HSI team's overall interaction with the larger program management and SE teams, with other (hardware/software) discipline teams, and with technical authorities. Implementation of an HSI team will vary between projects, as will the implementation of organizational and project support for HSI activities, so the HSIP affords an opportunity to document unique aspects for each project. The HSIP outlines the discipline's approach to risk identification and mitigation and how the HSI team will integrate with and/or utilize the program's risk and mitigation processes.

5.2.2.7 HSI Requirements Development and Analyses

Human Systems Integration includes the integrated and comprehensive analysis, design, and assessment of requirements, concepts and resources across the HSI domains. Together these domains define human interaction with other system components that impact operational effectiveness and an integrated requirements analysis can identify and address interdependencies and trade-offs that may be needed.

HSI requirements are the ultimate tool for influencing system design and performance, but they often also have cost and schedule implications. HSI requirements ensure the human is adequately considered during system design. These requirements generally focus on ensuring that the design accommodates for human performance characteristics and range across a wide array of technical domains (just as HSI includes multiple domains). Some such requirements maybe focused on health and medical concerns, some may relate to human interface design, while others may touch on maintainability and supportability.

HSI considerations can become requirements only if they are considered early in the project life cycle, with their resulting performance parameters expressed in quantitative terms. HSI requirements should be expressed as all other requirements are addressed in project system requirement documents, embedded within the design, and with associated KPPs and key system attributes. This allows HSI requirements to become measurable, which is necessary for effective implementation within the system life cycle.

NASA projects follow the iterative requirements definition processes described in NPR 7123.1, NASA Systems Engineering Processes and Requirements. However, additional standards and requirements may also be relevant to defining HSI requirements. It is incumbent upon the HSI Lead to seek out the applicable document(s) for the project being supported. Each standard statement defines a level of acceptable risk in a specific area. The Lead is responsible for working with requirement owners to decompose these into specific HSI requirements and managing cross-cutting requirements across the project and related systems based on the intended operation and system architecture.

5.2.2.7.1 Relevant Standards and Requirements

NASA program-level requirements are often based on higher-level standards and Agency-level requirements (e.g., NASA-STD-3001, NASA Spaceflight Human-Systems Standard; NPR 8705.2, Human-Rating Requirements for Space Systems; NASA- STD- 8709.22, Reliability, Maintainability, Supportability Definitions; NPR 7900.3D, Aircraft Operations Management Manual; NASA-SP-2007-580, System Safety Handbook, Volume 1; NASA-STD-8739.8A, Software Assurance and Safety Standard). Based on the NASA Mission Directorate sponsor of a program or project, different standards and requirements may be relevant to the project areas, e.g., human rating, airworthiness, safety, Ground Support Equipment (GSE).

For Human Space Flight (HSF) programs or projects, NASA-STD-3001 Vol. 1 and 2, NASA Spaceflight Human-Systems Standard, and NPR 8705.2, Human Rating Requirements for Space Systems, provide much of the primary basis for HSI requirements. ASA-STD-5005,Standard for the Design and Fabrication of Ground Support Equipment. NASA has endorsed FAA-HF-STD-001 for ground systems for human space flight and other NASA programs.

For aeronautics and aviation programs or projects, standards include MIL-HDBK-516C, Airworthiness Certification Criteria; FAA-HF-STD- 001B, Human Factors Design Standard; FAA AC25-11B, Electronic Flight Displays; SAE-6906, Standard Practice for Human Systems Integration; and NASA-STD-7009, Standard for Models and Simulations. Additionally, NASA-STD 8709.20, Management of Safety and Mission Assurance Technical Authority (SMA TA) Requirements, is related to an integrated set of HSI requirements. An example of a standard for aviation software requirements is RTCA DO-178C, Software Considerations in Airborne Systems and Equipment Certification, and its companion documents.

5.2.2.7.2 Developing HSI Requirements

How the HSI requirements are developed, integrated, interpreted, and verified is also of critical importance, and should include support from parties responsible for HSI, SE personnel, relevant project technical personnel, and discipline experts in each HSI domain. HSI requirements may be based on standards, but they also are derived from the ConOps via functional analysis of the mission, scope, relevant HSI domains, human risk mitigation, and task and system function allocation analyses, hence the need to include multiple perspectives and stakeholders in their creation. HSI design, functional, and performance requirements flow from a high level to specific and quantitative requirements to accommodate constraints imposed by human performance, but allow as much design/operations trade space as practical.

Requirements development is driven by the results of task, workload, and functional analyses of individual sub-systems, systems, and systems-of-systems and should reflect the cumulative effects of related systems integration. A task analysis identifies system- and subsystem-level tasks, to determine human requirements for project and mission objectives as described in Section 5.2.2.4.

5.2.2.7.3 Requirements Definition Process

The process of requirements definition is iterative and develops high-level system requirements, product requirements, and lower-level product/component requirements. The requirements should enable the description of all inputs, outputs, and required relationships between them, including constraints, and system interactions with operators, maintainers, and other systems. An overview of the process follows. For a more comprehensive description, refer to the NASA Systems Engineering Handbook, Vol. 1 and 2.

- Identify the inputs needed (e.g., baselined ConOps, task analyses, human/systems function allocation, Project MOEs)
- Identify constraints (those that limit system use, such as environmental conditions and technical standards). Constraints typically cannot be changed based on trade-off analyses.
- Develop use case scenarios – how the system will be used and/or operated.
- Identify systems and subsystems with HSI-relevant requirements (e.g., cockpit systems, LSS/ECS, avionics, ground operations, habitability).
- Define functional requirements.
- Define performance requirements.
- Define requirement rationale.
- Define requirements in acceptable statements (i.e., using *shall, should, will*).

Program and project requirement documents provide HSI requirements, such as those for ISS Crew Transportation and Services [ref. 28] (includes HSI requirements for CCP) and the Human Landing System [ref. 29]. An example of an HSI requirement for crew system interfaces follows.

HSI Requirement Example: HLS-HMTA-0012 Nominal Cognitive Workload

The system shall provide crew interfaces that, when used to perform nominal crew tasks, result in Bedford Workload Scale ratings of 3 or less (or equivalent rating on another validated workload scale).

Rationale: *Metrics of cognitive workload measure the mental demands required of a person to perform a given task. Appropriate workload levels keep the crewmember engaged while allowing spare mental capacity to deal with concurrent tasks or issues. Some of the most safety-critical decisions and actions associated with operating a spacecraft are carried out while the crew is multi-tasking; processing numerous inputs; and making decisions concerning multiple, possibly unrelated, problems. Work may also demand abrupt shifts between solo tasks and tasks relying on others' input. Likewise, environmental stressors such as radiation and altered atmospheric composition or pressure may impede the ability to adapt to changes in cognitive workload. Excessive workload demands on any one task can cause operators to focus exclusively on one problem or approach, leaving little or no capacity for other problems that may occur. Therefore, having designed a human-system interface to support a crew task, designers assess the operation as part of a HITL simulation to determine the associated workload. If the cognitive workload is judged to be so high that a human has little or no spare capacity for a concurrent problem, the task and supporting interfaces are to be redesigned. NASA uses the Bedford Workload Scale as the workload verification method for a number of program requirements. However, the NASA Task Load Index (TLX) may be preferred for developmental testing, due to its diagnostic properties. Other validated indicators of workload may be used by programs with approval from the Health and Medical Technical Authority.*

The example showcases how the system, the tasks performed using the system, and the execution of the task must all be structured to accommodate human workload capabilities, particularly in this case from a cognitive perspective, and assessed using an industry standard method that is relevant for aerospace. Note that this example is for nominal operations, and that there is another requirement for off-nominal operations (allowing for higher levels of workload under off-nominal conditions). Also note that verification approaches are equally critical, and the HSI Lead must ensure that agreed-upon verification objectives and methods are appropriate and sufficient.

HSI X-59 Aircraft Element Requirement Document Example
LBFD Project Aircraft Element Requirements Document (AERD) - DRD-SE-02-03_2004-1018

Crew Emergency Egress: Ground, In Flight

The Aircraft Element shall allow the pilot to evacuate the aircraft unassisted on the ground in less than 30 seconds with no life-threatening injuries.

Rationale: *NASA standard practice is to demonstrate that a crewmember of a high-performance aircraft can safely egress the cockpit in 30 seconds or less without the use of the ejection seat. The Airworthiness Requirements and Criteria document contains the NASA criteria.*

The Aircraft Element shall allow the pilot to perform emergency egress throughout the flight envelope.

Rationale: *The emergency in flight egress envelope is being defined to ensure the ejection seat will operate within this envelope.*

Maintenance

Engines Installed: The Aircraft Element shall provide access for routine servicing and inspection while the engine is installed.

Rationale: *NASA expects major aircraft systems and components will be easily accessed for service, inspection, removal and replacement/repair. Ground crew will need to service the oil tank, service the Variable Exhaust Nozzle unit, inspect the main fuel filter, check the igniters, and borescope the engine.*

Access to Mission Critical Data: The Aircraft Element shall provide maintainers access to safety and mission critical failure data recorded on the aircraft.

Rationale: *NASA will identify what equipment will record the safety and mission critical failure data and will inform the air vehicle contractor to allow ground access to download that data.*

[Reference 30]

CASE STUDIES: Development of HSI Requirements

D.1 Inadequate Consideration of Operations During Design: Shuttle Ground Processing

D.4 Cumulative Effects of Decision Making, Management Processes and Organizational Culture: The Genesis Probe Mishap

D.6 Effective Culture, Requirements and Trade Studies: The Reliable and Maintainable F-119 Engine

D.7 Inadequate Training, Procedures, Interface Design and Fatigue: The Collision Between Navy Destroyer John S. McCain and Tanker Alnic MC

D.8 The Cost of Untested Assumptions About Human Performance: The Case of the B737MAX

5.2.2.8 Developing and Using HSI Metrics

HSI Leads and practitioners use metrics to estimate and track the effectiveness of HSI implementation. Using quantitative metrics whenever possible makes HSI requirements measurable, which is necessary for effective implementation. To be effective, HSI metrics must be objective and verifiable and must be validated against system goals. Effective metrics can also reveal trends and identify where trade studies are needed.

Program-specific metrics may be developed by program management with support from the HSI Lead to track elements of system development that have high levels of management visibility because they pose significant risk to budget, schedule, or mission success.

Cost, schedule, risk, and performance, for example, are vital categories for characterizing HSI success. Key metrics often used as HSI indicators are operational resources (numbers of humans needed to make a system operational), personnel skill levels, and training. These metrics are defined and tracked in the HSIP (see Appendix A) for reporting of program cost and value during system design reviews. The HSIP metrics mature during the project life cycle, improving the significance of the metrics and showing trends in relation to program goals over time. Technical assessment is the crosscutting process used to help monitor technical progress of a program/project through periodic technical reviews and monitoring of technical indicators such as Measures of Effectiveness (MOEs), Measures of Performance (MOPs), KPPs, and Technical Performance Measures (TPMs). The reviews and metrics also provide information to support system design, product realization, and technical management decisions. KPPs are derived from overarching program goals and applied to a particular scope. Their use addresses program risk as to whether a design will accomplish its mission within the planned allocation of personnel or other resources/ constraints. It is important to outline the goals and scope an HSI KPP serves within the context of NASA to understand the HSI life-cycle impacts. KPPs can serve as an important metric to assess the effectiveness of a program's HSI implementation.

Consistent with this approach, a KPP could also apply to ground-based mission controllers and maintenance and logistics activities, expressed as a percentage of the human portion of cycle time in mission control or turn-around and launch preparation activities. These parameters are essential for providing required program capabilities and contributing to improvement, effectiveness, achievability, and affordability as part of HSI SE activities. The following is an example of a hypothetical KPP for the ISS, based on crew time.

Example KPP: Crew Time

An example of a KPP that can be applied to space systems is crew time. One of the most challenging parts of defining a crew time KPP is in determining threshold and objective values. The ISS crew has had to go 30 days without a day off to accommodate necessary tasks; therefore, the objective value should be conservative to protect for unplanned activities (particularly safety-critical ones) and maintain crew psychological health. The threshold value should likewise show significant improvement over the current ISS paradigm. If the baseline were to assume 2.5 out of 6 or 7 crewmembers' time would be devoted to maintenance, that yields the following:

Crew time required threshold value: No more than 40% of crew workday hours should be devoted to task preparation, scheduled and preventative maintenance, training and procedure review, and check-out of on-orbit hardware and software systems. The objective value is set at 35%. Crew workday hours are defined assuming the standards regarding personal time, exercise, and sleep remain the same independent of mission duration or destination and are exclusive of the abovementioned activities (e.g., task preparation, maintenance).

An Astronaut's Experience on Mir

"I learned that it is impossible to separate habitability issues from productivity in scientific research. They're one and the same … food, toilets, and a good layout of workstation space."

— David Wolf, Space News, 22, March 16-22, 1998

For programs or projects not associated with human spaceflight, such as aviation missions, other potential KPP metrics could be based on service time required to turn around an airplane after flights (varying by duration and mission), ground crew service time, parts replacement costs, or even service duration in days/weeks prior to suitability for the next flight. Likewise, robotic SMD missions with ground controllers may have KPP metrics associated with the number of personnel needed to manage the mission at any given time, perhaps varying by mission phase (e.g., approach to a celestial object of interest with many sensor or photography tasks vs. regularly quiescent transit periods between mission objects).

Additionally, to enable the system to meet its operational goals, KPP metrics should be generated for operators and maintainers associated with all types of missions (aviation, HSF, robotic) as well as facility projects. For example, KPPs could be applied to operators and maintainers in an air compressor station. KPPs can be used to improve operator and maintenance effectiveness and efficiency, assist with equipment and tool selection, personnel resource requirements (e.g., numbers of operators and maintainers needed to maintain system performance, skills and knowledge requirements, and training requirements), equipment installation design decisions, increase system performance, increased equipment reliability, and reduced risk and failure rates. Example KPPs related to maintenance include reliability of equipment, quality and speed of maintenance tasks, maintenance costs, and prediction of equipment failures.

An additional concept still in development that may be a source of HSI metrics is Human Readiness Levels (HRLs), which have been developed as human analog to Technology Readiness Levels (TRLs) [ref. 31]. The TRL scale is routinely used to measure a project's technical maturation, and its value is widely recognized. Over the last decade, the HRL scale has been developed to evaluate, track, and communicate a system's readiness for human use. The HRL scale is intended to complement and supplement the TRL scale. HRLs should provide a familiar systematic and consistent approach to measuring progress; focus on the readiness of a technology for human use; and fully incorporate the human element throughout the project life cycle. This scale has not yet been officially published by ANSI/HFES, but the release of ANSI/HFES 400-2021 "Human Readiness Level Scale in the System Development Process" is expected in late fall 2021. However, it is included here (see Figure 5.2-4) for reference and as a resource of potential value to activities, once it has been published and its adoption weighed in upon by NASA as an agency.

Level		Technology Readiness Level	Human Readiness Level
Production / Deployment	9	Operational use of deliverable	System successfully used in operations across the operational envelope with systematic monitoring of human-system performance
	8	Actual deliverable qualified through test and demonstration	Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users
	7	Final development version of the deliverable demonstrated in operational environment	Human systems design fully tested and verified in operational environment with system hardware and software and representative users
Technology Demonstration	6	Representative of the deliverable demonstrated in relevant environments	Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations
	5	Key elements demonstrated in relevant environments	User evaluation of prototypes in mission-relevant simulations completed to inform design
	4	Key elements demonstrated in laboratory environment	Modeling, part-task testing, and trade studies of human systems design concepts completed
Research & Development	3	Concepts demonstrated analytically or experimentally	Requirements for supporting human performance established
	2	Concept and application formulated	Human-focused concept of operations defined and human performance design principles established
	1	Basic principles observed and reported	Relevant human capabilities, limitations, and basic human performance issues and risks identified

Figure 5.2-4. Technology Readiness Levels and Human Readiness Levels

If adopted by NASA and DoD, HRLs may provide a simple common understanding on par with the TRL scale as part of project management to assess potential cost, schedule, and technical project/project risk associated with integrating the human with the machine/system.

5.2.2.9 HSI Verification and Validation (V&V)

The HSI team focuses on achieving functionally effective, maintainable systems that conform to applicable human performance characteristics. The success of the overall HSI V&V effort relies on the HSI Lead to confirm that the end product meets the system design goals.

To verify that a system design meets defined HSI requirements and validate that it meets the functional capabilities defined in the ConOps, the HSI Lead may use a combination of human-centered testing, modeling, and analysis. From an HCD perspective, such testing may include usability testing or HITL testing with mock-ups and simulations. Modeling and analyses may include cognitive modeling, task analyses, human error analyses, and 3D anthropometric or biomechanical modeling. The design tools found in Table 5.5-1 and Appendix G: HSI Resources, may be relevant during the V&V phases of the life cycle to demonstrate that the design process has complied with all applicable requirements and produced a verified and validated end product. Verification requirements should also include appropriate HSI-related evaluations or metrics, which helps to ensure their use in the program or project's engineering life cycle.

Beyond verifying that system requirements have been satisfied, validation from an HSI perspective will focus on system optimization and risk mitigation. Optimally usable systems result from successful management of system integration with human components. Early testing and evaluation help mitigate functional risks by validating appropriate system functionality. The scope of V&V activities largely depends on the nature of the project and system architecture, in that the system's relevant human characteristics may drive many aspects of human-to-system interface V&V (e.g., hardware and software interfaces). In a small-scale, simple project, the HSI requirements may focus on specific features of a hardware device that involve human visual interface (e.g., labeling or information displays) or manual interaction (e.g., switches and controls). In a more complex project, requirements may extend to driving the nature of function allocations among many humans, hardware end items, and software configuration items.

In each case, the HSI team must characterize system functionality in the context of the overall project mission-system design. In some cases, functional optimization may be characterized by human factors considerations such as usability, determined as a likelihood of design-induced errors when interacting with the system hardware/software, or by assessing user satisfaction with the system. The outcome of successful HSI V&V efforts will be a system that is verified to meet system requirements, while validating that the design also conforms to user needs in the context of the project mission defined in the ConOps. Through HSI, the end product system architecture can mitigate risk (i.e., human safety, health, and performance risk) to a higher degree than if HSI-related technical domain considerations not been taken into account, as lessons learned and technical domain concerns are addressed early and iteratively throughout the life cycle.

HSI Example: Commercial Crew Program

Modern complex systems typically require extensive HSI considerations. For the CCP, the HSI requirements document, "CCT-REQ-1130, ISS Crew Transportation and Services Requirements Document," was created to ensure that even when working with commercial vendors in a non-traditional manner, HSI requirements were a core aspect of system design processes and the project life cycle. CCT-REQ-1130 includes a wide array of requirements touching on each of NASA's HSI technical domains, including human factors engineering, safety, training, habitability and environment, maintainability and supportability, and operations, as well as a significant collection of health and medical concerns. The applicability of these NASA requirements were flowed down to the vendor's internal program requirements, and verification plans were drafted. Over the course of the final stages of design demonstrations, HITL tests, evaluations, and assessments were conducted to provide evidence of requirements compliance, which was documented in verification closure notices reviewed by NASA. As issues were identified, mitigations were agreed to between internal NASA SMEs and the CCP, and then between NASA and the vendor. Changes and maturation of the design occurred, and finally verifications were (or will be) considered complete *(note that vendor design verifications are still in progress at the time of publication)*.

CASE STUDY: HSI Verification and Validation

D.4 Cumulative Effects of Decision Making, Management Processes and Organizational Culture: The Genesis Probe Mishap

5.2.2.10 Lessons Learned

An important piece of information to bring to any Pre-Phase A (or other early life-cycle phase) is lessons learned from the operation of the original system or, in the case of new starts, the operation of similar legacy systems. The lessons learned capture system may be provided as an institutional resource or as a knowledge capture system provided for all projects by a NASA Center. If a relevant lessons learned system is not available to inform a project, the management team must endeavor to perform a literature search to identify applicable lessons learned, a time-consuming and often unsatisfying process.

Having an active knowledge-capture system running during the operational phases of NASA systems requires resources, strategic thinking, and persistence. Additionally, to enhance its usefulness, a lessons learned capture system should have guidance available to facilitate its use by new designers who may not know which lessons are best suited to apply.

As a best practice, personnel should invest time to query any available project knowledge capture systems for lessons learned applicable to their design challenge. Since it is impractical to learn "everything," personnel must rely on specialists and experts to avoid pitfalls and capitalize on previous successful implementations.

Capturing Lessons Learned for Future HSI Activities

"The wise learn from their own and others' frequent successes, as well as from infrequent mistakes."

— Dr. Jon Holbrook, Deputy Human Factors Technical Fellow, NASA Engineering & Safety Center (NESC)

For HSI Leads, strategically investing in and utilizing knowledge capture systems carries unique challenges given the large volume of previous work that must be leveraged to "insert" humans into system design. However, it should always be remembered that unlike other systems, the HSI Lead does not have the option to redesign the human to fit the system, but must understand the intricacies of building a product designed for interaction of the human element with every aspect of the system throughout its life cycle.

ISS Crew Comment Database

The ISS Program has implemented a Crew Comment Database, which can be searched for helpful comments from crew regarding a specific trend, device, procedure, etc. The reports from this database are a good source for lessons learned for new designs, or for the "extended Ops" phase where changes need to be made to existing hardware to meet new mission objectives.

(For access to Crew Comment Database results, contact the ISS Program Office at JSC.)

HSI should strategically strive to identify consistent KPPs that may become common across project types. Doing this will not only help clarify basic duties required of the HSI Lead and a successful HSI effort, but having consistent metrics will also help build a database that could demonstrate HSI's ROI and collect lessons learned for the practice of HSI.

Large and successful projects typically become long-lived with extended operations phase(s), often with modifications performed to systems to extend original objectives and systems life, add new capabilities or mission objectives, and accommodate unexpected behaviors. Extensive systems upgrades or refurbishment often start the SE process back at an early life-cycle phase, usually Pre-Phase A. And of course, the startup of any new program or project begins at Pre-Phase A. The HSI Lead can use the HSIP to document specific HSI goals based on lessons learned to ensure those goals are given their proper significance to influence design.

5.3 HSI in the Acquisition Process

The majority of NASA's Programs and Projects are executed using a blend of NASA personnel, contractors, and third parties serving roles in some level of management and providing expertise in the areas of systems engineering and other specialty technical areas, including HSI. Outside parties are acquired through a variety of mechanisms (contracts, agreements, etc.) to provide tangible products and/or services. NASA acquires these products and services in accordance with the Federal Acquisition Regulation (FAR) and the NASA FAR Supplement (NFS). One way to ensure HSI is incorporated in NASA acquisitions is through timely involvement in the procurement process, from the earliest identification of a requirement through selection. In the absence of integration between key decision points and acquisition milestones, costly workarounds are inevitable. Given the Agency's commitment to include HSI in all facets of administration and management, developing acquisition strategies to meet HSI domain needs is essential. This section gives an overview of the NASA acquisition process, and how HSI considerations are incorporated in that process.

Most acquisition processes follow four basic steps: (1) market research and acquisition planning; (2) requirements and solicitation development; (3) solicitation; and (4) evaluation and award. NASA is no different. It is during these phases (i.e., market research, acquisition planning, and requirements development) that the most benefit is realized when it comes to effective HSI implementation.

Even before acquisition planning efforts begin, an HSI Lead should be involved in program or project conversations around whether the best solution is to "make or buy" and the critical decisions related to how efforts will be implemented and managed. The NASA SE Expanded Guidance, Volume 2, states that the NASA technical team remains responsible for SE throughout the acquisition life cycle and will contribute heavily to SE decisions and results no matter the acquisition strategy or composition of the technical team. Similarly, it is recommended that the NASA HSI team remain responsible for executing the program or project's HSI efforts.

For acquisitions with estimated values of $50 million or more, a requirements development team (RDT) is appointed to the acquisition. The RDT membership includes the technical team (functional and Center owners), contracting officer, resource analyst, small-business representatives, legal, property, security, and safety and health. RDT responsibilities and actions include, but are not limited to, conducting market research prior to developing a performance work statement (PWS); analyzing current and expected work content and assessing risk; and defining and preparing requirements and supporting documents (e.g., PWS, data requirements, government furnished property, mission/quality assurance requirements, independent Government estimate, funding profile).

Per NFS 1807.104(a), *"The acquisition planning team shall obtain input from the center offices responsible for matters of safety and mission assurance, occupational health, environmental protection, information technology, export control, earned value management, small business, and security to ensure that all NASA acquisitions are structured in accordance with NASA policy in these areas."* Here, the acquisition planning team is being directed to obtain input that will cover concerns in the listed areas. In the broadest sense, but not explicitly, HSI domains are represented. Having a representative from the HSI community on the acquisition planning team gives a voice to the entire domain and not just the subset listed here. Note: For acquisitions below $50 million, market research, acquisition planning, and requirements development are performed in a manner appropriate to the size and complexity of the acquisition. Prior to soliciting the Government's need, the RDT transitions to a source evaluation board (SEB), the primary group that prepares the solicitation and evaluates proposals.

The solicitation should contain all HSI requirements identified during acquisition planning and requirements development. From the onset, procurement products must contain language to support HSI. This early work is important to establish clear agreements with projects regarding the tasks and roles humans will take, which is critical to driving requirements. To the extent possible, the HSI Team should influence this planning and documentation. At a minimum, the HSI Team should document internal assumptions and begin tracking watch items early. The HSI Team must assess procurement activities to ensure the groundwork is laid for proper implementation of HSI. Depending on requirements, contractors may hold responsibility for aspects of design and development that are critical to HSI.

HSI Team members must provide inputs into the PWS and provisions, clauses, and deliverables, as appropriate, to capture these activities and products. Examples include ensuring there is adequate NASA insight into design and development; capturing appropriate approval authority for milestone reviews, requirements, and verification processes; negotiating with projects for the inclusion of appropriate content in data requirement descriptions or equivalent data delivery for critical products such as Task Analysis and Human Error Analysis; inclusion of appropriate developmental testing including HITL demonstrations and tests; and inclusion of HSI in proposal reviews and down-select processes. All products are ultimately listed in the Data Requirements Descriptions (DRDs); see Appendix F for examples.

DRDs can play a critical role in HSI implementation. As contractually required deliverables tied to specific milestones, DRDs provide formal documentation of analyses and processes that ensure insight for NASA, including HSI personnel. HSI leadership must work with project management early in the procurement phase to ensure appropriate HSI-relevant DRDs are included.

It should be noted that appropriate DRDs for inclusion depend upon a variety of factors, and a thorough discussion of these is outside of the scope of this document. Some primary considerations that should drive DRD development include technical project details, such as expected human-system interfaces; contract approach, including phasing of procurement; assignment of design element responsibilities; and level of NASA insight and oversight into in-progress design work.

A DRD delivered at a milestone after the completion of work may not provide NASA with insight early enough in the design process to make important impacts. Contract phasing is also a particularly important consideration; lessons learned from the CCP show that inclusion of HSI DRDs at late contract phases led to disagreements between NASA and contractors regarding what was expected and what was sufficient for verification closure. Program management may have reason to limit the number of contract deliverables; in cases like these, it will be important for the HSI Lead to ensure that important HSI-relevant deliverables are captured within existing DRDs, some of which may be owned by other teams.

An example of a fairly comprehensive list of DRDs for a large human spaceflight project might include the following:

- HSIP
- Labeling Plan
- Acoustic Noise Control Plan (ANCP)
- Task Analysis
- Worksite Analysis
- Human Error Analysis
- Information Design Analysis
- Developmental HITL Test
- Anthropometric Analysis
- Crew Operating Loads Analysis
- Vibration Analysis
- Vehicle and Systems Chemicals
- Ionizing Radiation Exposure Analysis

Examples of language for each of these DRDs are provided in Appendix F. These examples are intended to serve as a reference or starting point and must be tailored for each project. There may be many ways to reconfigure, combine, or expand on these example

DRDs, and there may be gaps in areas such as operations products that are not covered within the scope of these examples.

The HSI Team is responsible for developing and maintaining the NASA Program or Project HSIP. Prime contractors may also be responsible for separate contractor HSIPs. The HSIP should be drafted early in the life of the project and the initial product, similar to a Systems Engineering Management Plan (SEMP), should be delivered as part of the Request for Proposal (RFP) setting contractor expectations based on strategy decisions made during formulation. Ideally, NASA and a prime contractor would have separately maintained, yet integrated, HSIPs to cover each organization's role in HSI, their teams, and the strategies and approach to implementation and communication of HSI issues and risks. However, if the program or project elects to maintain a joint HSIP for the contractor and government roles in HSI implementation, the HSIP should clearly delineate responsibilities and authority and add contractor management signature authority to the title page included in the HSIP Content Template in Appendix A.

HSI contributions to requirements development and V&V processes are of utmost importance. Requirements must be established with the project, typically tailored from Agency standards based on project-specific ConOps and mission assumptions. The process will vary among projects, but it is the responsibility of the NASA HSI Lead to ensure that appropriate requirement and V&V strategies are documented. There may be further interaction with prime contractors to clarify requirements; negotiate changes;

Commercial Crew Transportation Capability (CCtCap) Example

NASA awarded two firm fixed price Commercial Crew Transportation Capability (CCtCap) contracts to Boeing and Space-X. These contracts are to design, develop, test and evaluate a crew transportation system, capable of safe delivery of crew to and from the international space station. See below Clauses H.15 Government Insight clause, paragraph (d)(1) and (d)(2) (i.e., HITL assessments of operational suitability), and DRD 001, Insight Implementation Plan: (d) Joint Test Team (JTT) Activities

(1) The JTT-related activities will be Contractor-led (ref. CCT-PLN-1120, Crew Transportation Technical Processes, Section 5.3, Flight Test), and shall include active and steady state Government participation both on site and remotely. The Contractor shall accommodate Government personnel, who will provide embedded insight during the activities identified in (d) (2).

(2) The Government's JTT insight activities will focus on qualitative assessments of crew operational interfaces with the vehicle and HITL assessments of operational suitability. These assessments will include, but are not limited to vehicle handling qualities, situational awareness, workload and operational complexity, usability, cockpit layout, displays and controls, and flight crew suits. In addition, insight will occur through participation during the planning and build up phase of ground testing (e.g., simulator training and evaluations, mockup demonstrations, etc.), during test flights, and during the post-test flight evaluation process. Insight gained through integrated operations assessments will ultimately feed into NASA's verification approval decisions (before test flight) and validation approval decisions (post test flight).

DRD 001, Insight Implementation Plan, section F.(b)(3) The approach to implement a Joint Test Team (JTT) for the planning and execution of flight test activities, including how they are incorporating Government flight and ground personnel in qualitative assessments of crew operational interfaces with the vehicle and HITL assessments of operational suitability; development of operations products; development of flight test objectives and plans; post-flight evaluation; and any other activities.

and consider any waivers, deviations, and exceptions. The NASA HSI Lead serves as a resource to coordinate expertise and integrate across HSI domains that may reside in different NASA organizations. The NASA HSI Lead must also give inputs through the appropriate approval authorities with regard to requirements and their V&V, including recommendations for or against updates and insight into the risks associated with any decisions.

Projects may include human-centric developmental or operational testing as part of their process. The NASA HSI Lead/Team should contribute to these efforts either directly or by providing appropriate levels of oversight and/or insight, depending on contract structures. NASA can provide expertise regarding appropriate use of HITL demonstrations and tests, and should ensure that results of testing impact designs and operations appropriately. Iterative testing leads to higher confidence of success at verification, and is intended to identify risks to human health and performance.

The FAR and NFS provide specific guidelines on the acquisition of goods, services, or innovation research and technology. Regardless of contract type, an assessment of HSI applicability is necessary to determine if HSI clauses should be included in the contract. Clauses on how HSI must be implemented should clearly state the Government's needs relative to the contract.

Excerpts from contracts follow, as examples of HSI clauses.

Engineering Services Contract Example

See PWS Section 2.1, which references "human factors" and NPR 7123.1 (which addresses HSI and incorporates NASA/SP-2015-3709, *Human Systems Integration (HSI) Practitioner's Guide*).

PWS Section 2.1 states, in part: *The Contractor shall provide design products and services in areas such as propellants, gases, electrical power, systems engineering and integration, reliability,* ***human factors****, cryogenics, hypergolic, pneumatics, hydraulics, fiber optics, communication systems, information technology security systems, sensors, instrumentation, hazardous gas detection, intelligent systems, modeling and simulation, computer hardware, software, networking, system safety, maintainability, contamination control, control systems, mechanical systems, structures, stress and load analyses, vibroacoustic analyses, thermal analyses, computational fluid dynamics, data analyses, industrial engineering, materials science, electronic design, data acquisition, metrology, and atmospheric science. The Contractor shall apply current state of the industry design techniques in the development of new systems and equipment. The Contractor shall perform development of modifications to existing ground systems and equipment.*

The Contractor shall meet the requirements of NPR 7123.1, NASA Systems Engineering Processes and Requirements, for the design and development of systems. Software produced under this contract shall be developed, documented and maintained in accordance with NPD 2820.1, NASA Software Policies and NPR 7150.2, NASA Software.

HSI in the acquisition process at NASA is continuing to evolve with new spaceflight projects and soon with other mission types. It is expected that the acquisition information provided within this handbook will continue to expand in depth and breadth as HSI implementation becomes more widespread within NASA and best practices begin to emerge from the community.

CASE STUDIES: HSI in Acquisition

D.4 Cumulative Effects of Decision Making, Management Processes and Organizational Culture: The Genesis Probe Mishap

D.6 Effective Culture, Requirements and Trade Studies: The Reliable and Maintainable F-119 Engine

5.4 HSI in the NASA Project Life Cycle

The goal of HSI in the Project Life Cycle is to balance total system safety and effectiveness and ensuring mission success as stated in Section 2.3. The approach is interdisciplinary and comprehensive throughout the product life cycle. HSI is applied to system design and development processes, system production and delivery of product(s), all operations phases, and decommissioning. HSI activities include management and technical processes that work within SE and complementary SMA and HMTA processes and methodologies to ensure success. A high-level, summary example listing of HSI activities, products, and risk mitigations by life-cycle phase is provided in Table 5.4-1. This table should also be tailored for the project for publication within the HSIP, as shown in Appendix A.

Table 5.4-1. HSI Activity, Product, or Risk Mitigation by Program/Project Phase

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
Pre-Phase A	**Concept Studies**	• HSI Lead selected and assigned during pre-formulation phase • HSI effort planned, scaled and tailored • Initiate draft HSIP • Contribute to ConOps development (include training, maintenance, logistics, etc.) • Contribute to early studies/analyses (task analyses, function allocation) • Review Supportability Plan • Identify domain POCs, develop network to support HSI role in subsequent program activities • Support development of AoA Study Plan or similar effort, to include drafting HSI conditions and constraints • Decompose applicable standards from NASA-STD-3001 as needed to develop draft Human Systems Requirements • Develop HSI inputs to requirements for mission, science, and top-level system, using applicable models • Provide HSI inputs to design solutions, technology and maturation strategies • Support development of draft Occupational Health Strategy/ Approach, as needed • Contribute to initial set of MOEs • Support development of Operability Study Report • Develop initial concepts for decomposition • Support development of products used for human assessments • Develop initial definition of human-centered metrics • Participate in development of verification and validation reports • Support architecture and mission trade-offs and analysis

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
Phase A	**Concept & Technology Development**	• Update HSIP (Baseline) • Provide inputs to ConOps (Initial) • HSI Team identified before SRR • Develop models and mockup(s) for HSI evaluations • Human Workload Evaluation Plan • Function allocation • Validation of ConOps (initial planning) • Provide HSI-centric input to document development efforts • Evaluate draft Reliability, Maintenance, and Support strategies for appropriate HSI equity, recommend input as appropriate. • Participate in test and evaluation (T&E) strategy development (prioritize HSI domain requirements for chosen material solutions, verify process for HSI domain requirements verification) • Participate/inform Safety Analysis Process • Provide input to RFP: SOW, SRD, SEMP: HSI-related requirements and verification methodology • Support drafting of program documentation insert HSI language as appropriate • Participate in Program Risk Assessment activities • Baseline Human System Requirements • Develop derived requirements to develop lower level design • Support development of baseline Occupational Health Strategy/Approach, as needed • Support identification of MOEs captured to drive MOPs and TPMs • Draft procedures • Verify and validate phase product end-items • Develop LLC estimates, as needed • Track HSI domain risks, as needed • Conduct human-centric assessments for established architecture • Conduct human error analysis
Phase B	**Preliminary Design & Technology Completion**	• Update HSIP to include HSI-related concerns from technical reviews, safety and health risk and strategy • Provide inputs to ConOps (Baseline) • Develop engineering-level mockup(s) for HSI evaluations • Define flight crew environmental and health needs (Aeronautics Research Mission Directorate (ARMD) and Human Exploration and Operations Mission Directorate (HEOMD)) • Develop HITL usability plan • Support development of Human-Rating report for PDR (HEOMD) • Provide HSI-centric input to support SRD/Systems Performance Specification development • Provide HSI input as required for Acquisition Strategy • Developers to verify HSI considerations environmental impact • Remain engaged with Risk Assessment activities, update HSI activity • Provide input for development of Product Support Strategy

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
		• Review System Test Reports, identify HSI concern with M&S outputs, mock-up test, and first article testing • Participate in test and evaluation review • Support development of manufacturing, logistics, training, and testing plans • Update HSI inputs to maintenance and logistics planning • Review Safety Analysis for accuracy, identify HSI opportunities • Update Human System Requirements • Support updates to the Occupational Health Strategy/Approach • Develop refined MOPs • Define and track TPMs • Develop plans/processes for integration of lower-tier products • Use models and prototypes for system design evaluation • Conduct task analyses • Update human error analysis • Develop project risk management plans • Provide HSI project feedback iterations
Phase C	**Final Design & Fabrication**	• Update HSIP to include inputs to training and operational phases • Conduct First Article HSI Tests • Support development of Human-Rating report for CDR (HEOMD) • Review Integrated Test results and identify concerns and recommend corrective actions, leverage result for HSI modifications • Provide HSI input to Acquisition Program Baseline • Update strategy related to incorporating HSI/update HSIP • Monitor Test planning, ensure HSI risks are addressed • Monitor/track ongoing analysis for HSI opportunities; update input as required. • Provide updates based on test results as required • Review Maintenance Task Analysis and Procedures • Update Human System Requirements • Update task and human error analyses • Update HITL usability plan • Begin developmental HITL Usability Testing • Support the update to the Occupational Health Strategy/Approach • Update manufacturing, logistics, training, and testing plans • Finalize design updates based on human assessments • Integrate HSI inputs evolved from individual component inputs • Integrate lower tiered products • Provide verification results to show that system models/prototypes satisfy requirements prior to production • Provide validation results to show that system models/prototypes satisfy operational intent • Update project risk management plans for production and operational risks • Assess detailed design to determine suitability prior to production

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
		• Provide HSI process feedback iterations
Phase D	**System Assembly, Integration & Test, Launch & Checkout**	• Support Human-Rating report for ORR (HEOMD) • Validate human-centered design activities • Validate ConOps • Verify and Validate Human System Requirements • Provide HSI input to system-level test plans/flight test plans • Provide requirement verification closure reports and product validation reports from HITL test/demonstration and from HSI inspections and analyses • Develop system-level and/or flight test reports that provide validation of analytical models used to predict system performance • Provide HSI inputs to operations and maintenance manuals, procedures, and training packages • Provide HSI inputs to system design data books and other supporting technical materials for use during Phase E • Validate HSI analytical models of the end-product system • Provide HSI inputs to the system certification package and to project risk management plans updated with all prelaunch mitigations
Phase E	**Operations & Sustainment**	• Monitor of human-centered design performance • Review HSI-related incidents and mishap data reports, provide input and constraints for modifications • Solicit user feedback, participate in HSIWG to highlight HSI opportunities • Review Failure and Discrepancy reports, ensure domain SMEs review relevant reports, provide input for trade-off analysis • Update strategy for merging HSI risk management into SE • Document achievable HSI requirements for each incremental stage (if evolutionary acquisition) • Update HSIP as needed • Ensure inclusion of HSI risk and strategy into safety documentation • Ensure HSI analyses, impacts and deficiency data is considered as part of modification/upgrade framework • Review Maintenance and update maintenance procedures • Develop HSI TPM Final Report • Provide HSI input to Flight Test Reports • Validate HSI models based on flight data • Document HSI Lessons Learned • Develop technical reports on human system operations
Phase F	**Closeout**	• Provide Lessons Learned report • Provide HSI input to decommissioning and disposal plan

Inherent to the rationale of emphasizing HSI in SE is accepting that all engineering is performed to fulfill human needs and accomplish human objectives. People are inherent to the success of any system; i.e., every system includes those who use the system to fulfill objectives. It is critical to consider users, maintainers, and operators as key components. Humans are the most resilient part of any system and can adapt, if possible, to sustain safe operations and mission objectives. As with all other components, however, humans have inherent performance characteristics. Acknowledgment of these, in the form of early planning and system design, greatly enhances the chance of mission success. However, human social and biological needs drive behavior in complex ways that are highly sensitive to context and experience. Performance that may appear initially to reflect an inherent limitation may instead reflect performance that is well-adapted for some environments or situations, but poorly adapted for others.

For example, the same capability for generalized learning that enables humans to successfully adapt to novel situations also creates challenges for sustained vigilance of rare events. That is, humans learn from their experiences when and how to apply cognitive resources such as attention. Sustained monitoring for rare events is an often-cited example of a human "limitation," but in actuality reflects a highly sensitive learning mechanism that does not reward allocating "costly" cognitive resources to a task with a highly unlikely reward. A computer chip does not learn, but in the case of "machine learning," algorithms can be programmed with a reward structure that disregards event likelihood, resulting in automation that can sustain monitoring for rare events by being insensitive to the contextual cues from which humans learn. Training is one method of addressing misalignments between human adaptability and mission objectives, but it is most effective when lessons learned during training are reinforced by operational experience. Training may need to be refreshed more frequently as the alignment between what is learned in training and from experience diminishes, and a comprehensive system perspective would account for this. Success in system design hinges upon the designers' ability to appropriately account for human performance, because in many cases, human "limitations" and "capabilities" are contextually dependent rather than inherent, immutable human properties.

Overarching risk reduction is another significant focus of HSI. It can be accomplished through review of related assessments and examination of lessons learned from predecessor efforts. These practices help resolve complex HSI issues that may require leveraging trade-off actions to optimize the desired capability. All overarching concerns identified should be comprehensively documented and monitored in the project's formal Risk Management framework until satisfactorily resolved. The risk identification process should take into consideration interactions between HSI domains.

HSI Leads may be tasked with applying HSI goals to life-cycle processes that have been tailored to a specific project. In many cases, the outcome will be an incremental development model that produces the system's initial capability early, followed by iterative cycles of feature development and product refinement. HSI is traditionally iterative in nature—a key practice is the establishment and maintenance of communication and feedback loops between designers and HSI domain stakeholders.

In an incremental development environment (e.g., Agile software development), phases may be distinct or may overlap. They may also be plan-driven from a mature set of initial requirements, experience-driven based on experiences gained from interaction with the initial capability system, or a combination of both. The goal of incremental development is to decompose the effort into smaller, manageable, and deliverable development of useful and high-quality products. By developing in increments, systems gain maturity through continuous integration and V&V, and development teams gain flexibility through early identification of risks and defects and early incorporation of end-user feedback.

To balance HSI's objectives of early stakeholder engagement and focus on human-centered design with the flexibility and fluidity of an incremental approach, practitioners and teams are required to be cohesive, communicative, and committed to meeting customer expectations, see Figure 5.4-1 [ref. 32].

An iterative design may use swiftly moving processes, but the primary focus is ultimately to design the system the customer needs within project constraints. NASA projects require rigorous attention to safety as a design consideration essential to mission success. Successful incremental design environments within NASA have tailored design processes to the NASA culture, creating hybrid life-cycle models that combine elements of incremental development with more traditional, plan-based development to give customers visibility into design considerations for safety, operability, and cost-effectiveness.

In addition to processes for developing high-quality systems, system usability processes are essential for ensuring stakeholder buy-in and mission success. Usability analyses and usability SMEs help mature early-stage system functionalities into later-stage design optimizations. This allows methods based on producing early hardware/software components to integrate the human during the complete development effort while consistently influencing design refinements throughout the life cycle.

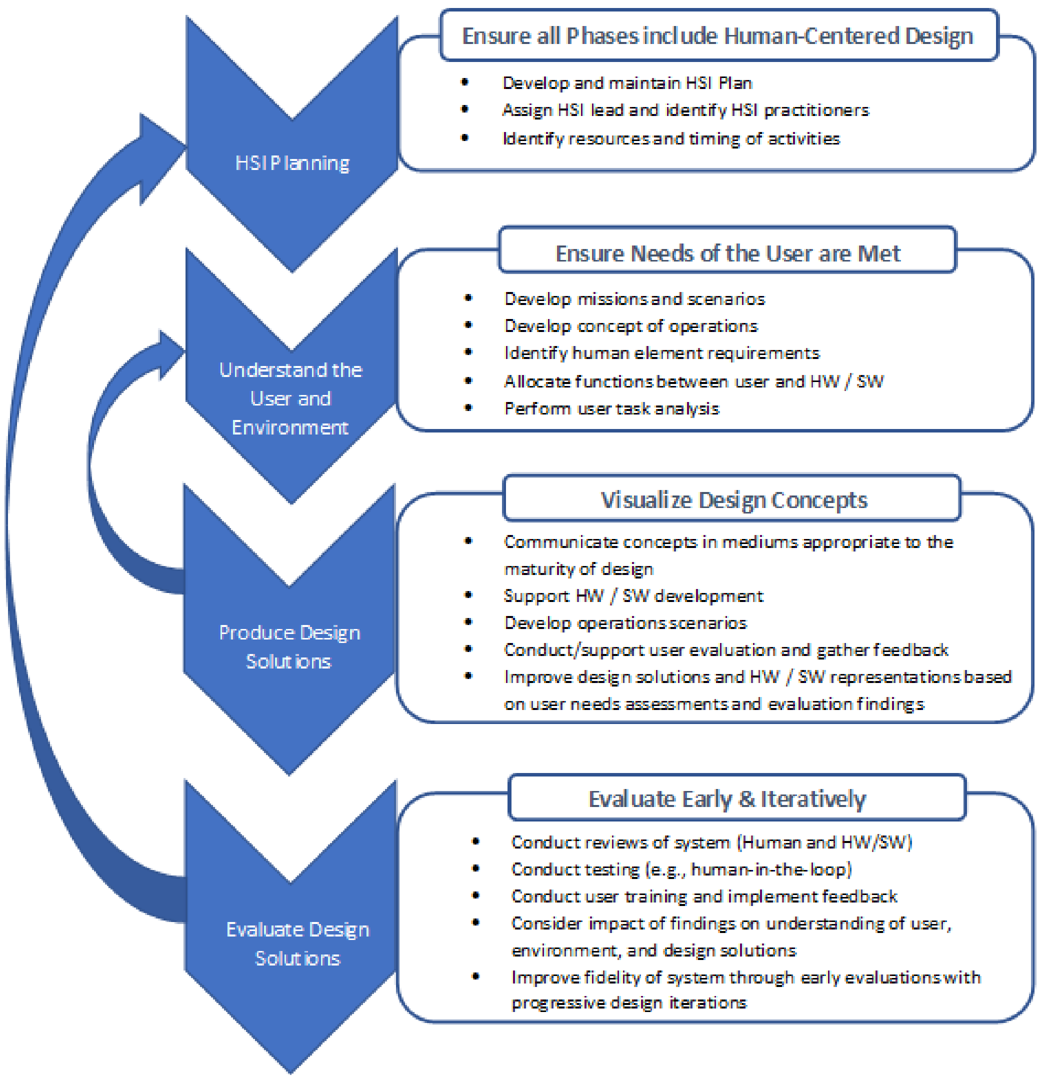

Figure 5.4-1. Systems Engineering – HSI Interaction: Human-Centered Approach (adapted from NASA Human Integration Design Processes)

HSI and Systems Engineering are tightly coupled, and to optimize impact, these and complementary SMA and Health and Medical activities must start in the early phases of any project. In this section, opportunities to recognize and manage HSI while drafting project and engineering documents during early phases and at major phase key decision points will be discussed. The approach will incorporate NASA SE processes, SE activities, complementary activities and life-cycle phases.

5.4.1 SE Processes and Corresponding Activity Overview

The 17 NASA SE processes are detailed in NPR 7123.1. The Systems Engineering Handbook shows how the SE processes are integrated within each life-cycle phase and repeated across multiple phases. The handbook and NPR are useful resources when drilling down into SE process flow details.

This document's approach uses NASA SE processes and SMA activities to execute HSI activities and products. Table 5.4-2 lists the 17 SE processes and corresponding SMA and Health and Medical activities and maps them to HSI points of emphasis.

Table 5.4-2. Mapping HSI with SE Processes and Corresponding Health and Medical and SMA Activities

Systems Engineering Processes	HSI Emphasis	Corresponding Health & Medical Activities	Corresponding SMA Activities
System Design Processes			
Requirements Definition Processes 1. Stakeholder Expectations Definition 2. Technical Requirements Definition	Function allocation between and among systems and humans, defining roles and responsibilities, developing requirements, baselining ConOps with functional and behavioral expectation, establishing MOEs, contributing to Operability study report, defining design and product use constraints, defining and evaluating TPMs for human performance, developing HSI and domain requirements	Determine applicability of Human Systems Standards from NASA-STD-3001 to program/project for requirements definition for supporting crew health and providing medical services	Design for Reliability, Maintainability, and Supportability Design for Safety Occupational Health and Safety (NPR 1800.1) Design for survivability
Technical Solution Definition 3. Logical Decomposition 4. Design Solution Definition	Function allocation (during decomposition), verify/validate the design solution against the ConOps, refine requirements; form and derive human requirements, iterative human-centered design, task analysis, design prototyping for HITL evaluation, operate-to documents, define and validate logical decomposition models (e.g., operator tasks) for derived requirements, mature detailed design, manufacturing, and testing plans, determine verifications including adequate HITL testing needed for verification and risk reduction	Tailor health and medical requirements as appropriate Determine verifications including adequate HITL testing needed for health and medical verification and risk reduction	
Product Realization Processes			
Design Realization Processes 5. Product Implementation 6. Product Integration	Validate design for all human systems interactions as elements are integrated, produce early-phase reports, mockups, models, prototypes, and demonstrators (and support their integration), generate and update detailed implementation plans and procedures, ensure solution is compatible with integration philosophy, review/generate detailed integration plans and procedures	Support as needed for any design validation, human rating or occupational health evaluations	SMA activities as defined in NPR 8705.2 (Human Rating) and/or NPR 8705.4 (Robotic) and delineated in the SMA Plan(s) Support as needed for any design validation, human rating or occupational health evaluations
Evaluation Processes 7. Product Verification 8. Product Validation	Verify the human-centered products in the context of the overall system to ensure it operates as designed, HITL testing, validation to ConOps, prepare to conduct verification; conduct trial verification for high-risk items, conduct verification of human system requirements, validate the human-centered products in the context of the overall system to ensure it captures the valid relationship with the rest of the system, evaluate design solutions against ConOps, complete validation events that demonstrate the end	Support of any HITL testing and validation of Con Ops or other evaluations relating to human health	

	product meets user needs in accordance with ConOps		
Product Transition Processes 9. Product Transition Process	Preparing for operations: training, simulations, handing and operations documents, provide HSI input to the technical reviews that support transition of the end product to its intended user for operations, generate HSI objective evidence of the acceptability of the end product and its operational mission	Support for development of health and medical training and operations products	
Technical Management Processes			
Technical Planning Processes 10. Technical Planning	LCC management, produce HSI content for SEMP, HSIP, and other technical plans	Assessment of human health risk and mitigation	SMA planning and requirement formulation SMA feedback to other key program/project planning and requirements medium Risk-informed decision making support (e.g., PRA, FMEA, Hazard Analysis)
Technical Control Processes 11. Requirements Management 12. Interface Management 13. Technical Risk Management 14. Configuration Management. 15. Technical Data Management	HSI participation in management processes (as required), assess and create mitigation plans for HSI domain risks, conduct technical risk assessment; implement mitigation plans, HSI Team produces HSI Technical Lessons Learned	Ensure all human involvement/ impacts are captured within appropriate documentation HMTA feedback to other key Program/Project Planning and Requirements	
Technical Assessment Process 16. Technical Assessment	HSI products, entrance, and exit criteria for milestone reviews; TPM examples; assess product against plans and requirements, analyze operational aspects that affect human users/maintainers to determine where the system is fully successful or needs improvement	HMTA review and approval of milestone reviews and products	
Technical Decision Analysis Process 17. Decision Analysis	Human-centered design, HSI domain participation, conduct decision analysis process for identified technical issues including HSI concerns	Risk--informed decision making with respect to human risk	

Tangible products from the HSI effort are necessary for communication and engagement with the project. Three primary products are the ConOps, HSIP, and HSI requirements, but they may not be the only HSI-related products or documents defined for a project. The HSI Lead can tailor the product set to meet requirements and stakeholder needs. For example, a maintenance or/maintainability plan may have to be developed for a critical system, including instructions to optimize human-machine interactions and ensure reliability and availability are not negatively impacted.

CASE STUDY: Life-Cycle Management

D.4 Cumulative Effects of Decision Making, Management Processes and Organizational Culture: The Genesis Probe Mishap

5.4.2 HSI in Safety and Mission Assurance

The safety and reliability of new and modernized technologies and systems ultimately depend on their interaction with end-users—operators and maintainers. Even the most sophisticated technologies, when designed and implemented without proper consideration of user needs and requirements, may not achieve optimal system performance because of mismatches between technology and human operator limitations or capabilities. To help achieve optimal overall system success, the human operator should be viewed as a central part of the system. Human operators make an essential positive contribution to system performance and resilience, and systems must be designed and implemented to take full advantage of human capabilities. Careful evaluation of an operator's interaction with a system, beginning at initial concept and design, can eliminate potential mismatches downstream during implementation and operation. Such considerations include:

- Accurately reflects the system through interfaces/simulators/guides/etc.
- Meets user needs and expectations
- Supports situation awareness and crew task performance
- Minimizes secondary tasks and distractions
- Balances workload
- Compatible with users' cognitive and physical characteristics
- Tolerant to error
- Simple to use (simplest design possible)
- Standardized and consistent throughout
- Provides timely information and feedback
- Provides a means to obtain explanations where needed
- Provides guidance and help
- Provides appropriate flexibility; adaptable to unique situations and personal preferences
- System demands are compatible with human performance characteristics
- System can detect, tolerate, and support recovery from expected and unexpected perturbations
- Restricts or blocks undesired behaviors
- Minimizes consequences of uncorrected errors
- Enables positive human contribution

For more information on HSI within Safety and Mission Assurance, see Appendix C.

5.4.2.1 HSI in Applicable SMA-Related Policies, Standards, and Guidelines

For crewed and human-rated missions, NPR 8705.2C, managed by OSMA, requires application of NASA-STD-3001 for human spaceflight and the FAA Human Factors Design Standard to human-rated programs/ projects. NPR 8705.2C also calls for establishing a formal HSI team for human spaceflight programs/ projects that results in human-rated space flight systems. As stated previously, it should be noted that this handbook is not fully aligned with the required NPR 8705.2C establishment of an HSI Team in composition or timeline; however, it is expected that

NPR 8705.2C will undergo revision later in 2021 to align with the guidance in this document.

For uncrewed/robotic missions, HSI involvement is more flexible in nature based on the objectives-driven requirements process delineated in NPR 8705.4. HSI can significantly improve effectiveness and efficiencies associated with things like requirements development, requirement flow-down, human-machine interfaces, and knowledge transfer, which can be instrumental in improving technical, cost, and schedule performance and reducing overall LCCs.

The full set of SMA directives, associated standards and handbooks supporting HSI related activities is available at:
https://sma.nasa.gov/policies/all-policies.

5.4.3 HSI in Health and Medical

Human capabilities, needs, and limitations must be considered in the design of the full life cycle of the system for successful performance of any system involving the human. As early as possible in the pre-definition or definition phase of a program/project the relevant human system standards should be consulted to determine what is applicable. For human exploration, NASA Spaceflight Human-Systems Standard, NASA STD-3001, should be consulted first. Health and medical experts provide unique expertise throughout the design, testing and operational phases regarding human physiology beyond the scope of other functional areas. Examples include: For space suits, the need for oxygen in both the correct concentration and pressure, and the management of work-rest cycles for control room personnel for deep space probes. Agency health and medical experts can assist in determining how best to tailor the health and medical standards appropriately for the specific application, need, and purpose of the mission or project.

As we expose humans to the challenging environments in which NASA operates and push the boundaries for exploration, health and medical concerns should be addressed for all humans with any interaction or association with the design, testing, building, and operations of the system.

Health and medical experts are a critical resource in the development and execution of operations concepts definitions, human-in-the-loop testing, and user evaluation testing to ensure verification and validation that human system requirements have been applied for all the relevant human system standards. Throughout these efforts, health and medical experts' support also applies to the products required to perform human rating evaluation. In addition, health and medical experts support all flight project-related occupational health evaluations.

Health and medical experts provide critical review and approval for all related milestones throughout the life cycle of the program or project and are responsible for assessing human health risk and advising on mitigation steps.

5.5 HSI Team Application of Tools, Models, and Analyses

HSI tools, models, and analyses are defined as any tool or procedure used to collect and analyze human-centric behavioral and performance data, perform HITL simulations and tests, measure HSI effectiveness, perform V&V assessment, or model human capabilities and system interactions. These tools are typically used to collect and analyze information that will assist in designing systems that require human interface in any of the HSI domain areas. Additionally, the HSI team may apply System Engineering (SE) tools, including software applications and processes, to HSI activities. These may vary in their overall capability, but should be capable of tracking design requirements, collecting and storing requirements data, and performing analysis.

The HSI Lead is responsible for ensuring appropriate technical models and tools are available so the project HSI team can accomplish its analytical work; however, the selection of tools and methods will depend on program constraints, including the phase of program development, relevant domain, and other constraints that are out of the HSI staff's control. The HSI Lead should include the necessary models and tools in the team planning and budgeting and ensure that the necessary SMEs are engaged to apply the tools. The broad scope of HSI means many models and tools may be candidates for application on a project, but a subset will be selected by the HSI team based on specific needs, processes, and budget. Some tools, such as computer-based human models, will involve a significant acquisition cost in addition to the need to budget for labor in applying the tool and analyzing the results. Other tools (such as rating scales) have zero acquisition cost, but still require budgeting for application and analysis. The tools to be applied in a project will be documented in the HSIP.

The mix of required HSI models and tools will change throughout the project life cycle as activities progress from architectural trades, conceptual to detailed design, risk analysis, system performance analysis, HITL testing and demonstration, system development, and mission operations. Results and analysis from HSI models and tools can be used in early-phase decision making for architecture, design, prototyping, and requirements, and in later phases can support V&V. For example, tools designed for diagramming, sketching, storyboarding and prototyping may be useful to use during concept development. Computer-aided design, 3D printing, finite element modeling, graphical design, structural design and dynamic simulation tools may be beneficial during design phases. Animations, virtual reality, visualization, usability testing and survey tools are often used during HITL testing and physiological monitoring and use of psychophysiological test batteries may be useful during operations. Human factors engineering tools often include use of biomechanical and human modeling, collection of motion data, fatigue risk assessment, and workflow management tools. Habitability and environmental engineering activities often make use of simulation tools for acoustics, vibration, lighting, dynamic loading, and radiation exposure. Task analysis and workflow automation tools can be useful within the maintainability and supportability HSI domain, and training development platforms and flight simulation tools are often used within the HSI training domain.

For a sampling of commercially available or government-developed tools and methods, see Table 5-5.1 and Appendix E for a more thorough list of available tools in use within NASA.

CASE STUDY: HSI Tools, Models, and Analyses

D.3 Expert Knowledge of Human Performance: Effective Countermeasure for Launch Vehicle Display Vibration

Table 5.5-1. Representative Examples of HSI Tools

General Type	Specific Examples
Prototyping	Axure RP 9, Figma, MS Maquette, Sketch
Computer-Aided Design	AutoCAD, Creo Parametric & Creo View
Usability Testing	Morae
Eye Tracking	COBRA, HTC Vive Pro Eye, Tobii Pro Glasses, Tobii Pro Lab, SmartEye, and Seeing Machine
Cardiac Monitoring	Bittium Faros
Performance and Workload Assessment	Multi-Attribute Task Battery-II, NASA TLX

Fatigue Risk	Aviation Fatigue Meter, Fatigue Avoidance Scheduling Tool (FAST)
Risk Assessment	TRIAD
Human Modeling	Jack, Process Simulate Human
Task Analysis	Behavioral Observation Research Interactive Software (BORIS), Blackbird, Improved Performance Research Integration Tool (IMPRINT), MindManager, Task Architect
Lighting Simulations	Adaptive Lighting for Alertness (ALFA), Optics Studio, Radiance
Acoustics & Vibration	COMSOL Multiphysics Software, VA One, Wave6
Flight Simulation	DAVE-ML, Flight Simulator, X-Plane 11
Training Simulation	Multi-Aircraft Control System (MACS)

5.6 HSI Resources

Resources available to the HSI team include NASA standards and documentation, standards and documentation from outside organizations, professional communities, and professional and standards groups.

5.6.1 NASA Standards and Documentation

NASA documents covering aspects of HSI include those outlined in Table 5.6-1.

Table 5.6-1. NASA Documents with HSI Content

Document	HSI Content
NASA Policy Directives/Procedural Requirements	
NPR 8705.2, Human-Rating Requirements for Space Systems	Processes, procedures, and requirements necessary to produce human-rated space systems that protect the safety of crewmembers and passengers on NASA space missions. For programs that require Human Rating, paragraph 2.3.8 requires the program to form an HSI Team before SRR.
NPR 8705.4A, Risk Classification for NASA Payloads	Lays out a framework for objectives-driven SMA requirement development based on accepted standards or NASA approved alternative. Framework allows for customization of related SMA activities to optimize HSI, as appropriate, as defined in SMA Plan(s).
NPR 7123.1, NASA Systems Engineering Processes and Requirements	Appendix A includes definition of HSI. Appendix G, Life Cycle and Technical Review Entrance and Success Criteria, includes an HSIP.
NPR 7120.5, NASA Space Flight Program and Project Management Requirements w/Changes 1-13	Establishes the requirements by which NASA formulates and implements space flight programs and projects, consistent with the governance model contained in NPD 1000.0B, NASA Governance and Strategic Management Handbook.
NPR 7120.11, NASA Health and Medical Technical Authority (HMTA) Implementation	Implements HMTA responsibilities to ensure that Agency health and medical policy, procedural requirements, and standards are addressed in project management when applicable and appropriate.
NPR 8900.1A, NASA Health and Medical Requirements for Human Space Exploration	Establishes health and medical requirements for human space flight and the responsibilities for their implementation including health and medical, human

	performance, habitability, and environmental standards; sponsorship of health-related and clinical research.
NASA Systems Engineering Handbook (SP-2016-6105) Rev 2 (companion to NPR 7123.1)	Describes SE as it should be applied to the development and implementation of large and small NASA programs and projects. HSI is mentioned in the context of incorporating an HSIP in program/project documentation. This document includes an HSIP Content Outline in Appendix R which lists HSI activities, products, and risk mitigation by life-cycle phase.
NASA Systems Engineering Expanded Guidance (SP-2016-6105 - SUPPL), Volume 2	HSI is explicitly described. Includes descriptions of HSI domains, life-cycle activities, products, procedures, and practices.
NASA-STD-3001, NASA Space Flight Human System Standard	OCHMO mandatory standard for NASA human space flight programs. Establishes Agency-wide requirements that minimize health and performance risks for flight crew in human space flight programs. – Volume 1 of NASA-STD-3001 considers human physiologic parameters as a system, much as one views the engineering and design of a mechanical device. Doing so allows the human system to be viewed as an integral part of the overall vehicle design process, as well as the mission reference design, treating the human system as one of many, working in concert to allow the nominal operation of a vehicle and successful completion of a mission. - Volume 2 focuses on human-system integration, or how the human interacts with other systems, including habitat and environment. Mission performance issues are highlighted—whether the human and the system can function together within the environment and habitat to accomplish the tasks necessary for mission success. Volume 2 is applicable to all human space systems. System developers are to write tailored design requirements that will ensure the end product meets requirements of Volume 2.
NASA-STD-8729.1A, NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems	Addresses human performance and HSI in the context of available activities (e.g., Human Task Analysis, Human Error Risk Assessment) to meet specific R&M objectives for missions ranging from Spaceflight Risk Classification A to Ground systems development.
NASA/SP-2010-3407, Human Integration Design Handbook (HIDH)	The HIDH can help with the preparation of the system-specific design requirements and is organized in the same sequence as NASA-STD-3001 Vol. 2 provides useful background information and research findings. The HIDH is a resource to understand the background associated with the standards to prepare program- or project-specific requirements. The HIDH can be used not only in the preparation of requirements but also as a useful tool for designers as it provides guidance for the crew health, habitability, environment, and human factors design.
NASA/TP-2014-218556, Human Integration Design Processes (HIDP)	HSI design processes, including methodologies and best practices that NASA has used to meet human systems and human-rating requirements for developing crewed spacecraft. HIDP content is framed around human-centered design methodologies and processes.
NASA/SP-2014-3705, NASA Space Flight Program and Project Management Handbook (companion to NPR 7120.5)	Contains context, detail, rationale, and guidance that supplements and enhances the implementation of space flight programs and projects, including an HSIP.

5.6.2 Standards and Documentation from Outside Organizations

Several military and civil publications deal with the practice of HSI. Documents that may be of assistance to the NASA HSI practitioner include:

- Department of Defense, Human Engineering Program Process and Procedures Handbook (HDBK-46855A).
- Standard Practice for Human Systems Integration, SAE International, 2019 SAE6906.
- Human Systems Integration (HSI) in Acquisition (Acquisition Phase Guide). Carr, L & Greene, F. (2009). Air Force Human Systems Integration Office Report AFHSIO-004.
- Booher, H. R. (2003). Handbook of Human Systems Integration (Vol. 23). John Wiley & Sons.
- Stanton, N. A., Hedge, A., Brookhuis, K., Salas, E., & Hendrick, H. W. (Eds.). (2004). Handbook of human factors and ergonomics methods. CRC press.

Human factors design standards are valuable sources of information. Two widely used standards are:

- MIL-STD 1472 – Design Criteria Standard: Human Engineering.
- FAA-HF-STD-001B – FAA Human Factors Design Standard.

A more extensive list of relevant standards and documentation can be found in Appendix G, HSI Resources.

5.6.3 Professional Communities

The following professional communities, although not open to all NASA personnel, can be valuable sources of information, support and networking:

- NASA HSI CoP (See Section 4.1 for additional information)
- NASA Human Factors Technical Discipline Team
- NASA Human Factors Task Force
- NASA Systems Engineering Technical Discipline Team
- NASA Model-Based Systems Engineering CoP
- NASA Life Sciences Technical Discipline Team
- Department of Defense Human Factors Engineering Technical Advisory Group
- DoD Joint HSI Working Group
- Defense Acquisition University (DAU) HSI Community of Practice (https://www.dau.edu/cop/hsi)
- DoD HSI Community of Interest

5.6.4 Professional and/or Standards Organizations

The following professional organizations promote HSI via events open to the public and/or the publication of standards and guidance documents.

- Board on Human-System Integration. National Academies of Science, Engineering and Medicine.
- NDIA (National Defense Industrial Association) Systems and Mission Engineering–HSI Committee
- IEEE Human System Integration Technical Committee
- INCOSE Human Systems Integration Working Group
- SAE Technical Committee G-45 Human Systems Integration

Appendix A. HSIP Content Template

A.1 HSI Plan Overview

The Human Systems Integration Plan (HSIP) documents the strategy for and planned implementation of HSI through a project's life cycle. By developing and implementing a comprehensive HSIP, the system will have the opportunity to run more smoothly and efficiently and decrease overall cost over time. The intent of implementing HSI principles and processes is to ensure:

- The human element of the total system is effectively integrated with the hardware and software elements within the operational context, such that the necessary interfaces among the system elements work in harmony to promote improved overall system design and performance.
- Human performance characteristics are considered as integral and critical system elements.
- All human capital required to develop and operate the system is accounted for in life-cycle costing.
- The system is built to accommodate the characteristics of the user population that will operate, maintain, and support it.

The HSIP is project-specific and a required document per NPR 7123.1 and NPR 7120.5 (for projects, single-project programs, and tightly-coupled programs). The HSIP should address:

- Strategy and approach for implementing HSI across the project life cycle, either through leadership or contributions to other technical efforts to ensure HSI principles are applied to each relevant project system or sub-system.
- Roles and responsibilities for integration across HSI domains.
- The organization of the HSI component, including the location (e.g., project office and/or contractor organization), and a summary of qualifications.
- Roles and responsibilities for coordinating integrated HSI domain inputs with the program/project and any working groups, committees, or boards and stakeholders.
- HSI goals and deliverables for each life-cycle phase, including identification of gaps and issues.
- Planned methods, tools, requirements, processes and standards for conducting HSI.
- Strategy for identifying, mitigating, and resolving HSI risks.
- Strategy for ensuring the HSIP is aligned with the SEMP.
- Strategy for maintaining the HSIP throughout the project life cycle.

The HSI Lead is responsible for the development, implementation, and maintenance of the HSIP. The HSI Lead (and team, if applicable) should develop the HSIP with coordination and support from the project manager and systems engineer.

When implementing HSI strategies, the HSI Lead should leverage the tools and products required by SE when applicable (e.g., ConOps development); function allocation analyses across the elements of a system (e.g., hardware, software, and human); requirements development, documentation, and tracking processes; processes for defining verification criteria, methodology, and artifacts; identification of measures of performance and system check-out (SCOs) processes; tracking; and scheduling to validate HSI requirements. It is not the intent of the HSIP or its implementation to duplicate SE plans, or any other project-required plans or processes. Rather, the intent is to define and document the unique technical expertise and effort needed to fully integrate human performance characteristics into the life-cycle process.

A.2 HSI Plan Content Template

The template that follows contains format and content guidance for the development of a comprehensive NASA HSIP, including embedded recommendations for tailoring the HSIP. Note that this HSIP template is a good starting point but may need additional information or subsections to address specific project needs.

[Program/Project Name]

Human Systems Integration Plan

[short title or acronym]

____ ___________

Engineering Technical Authority Date

____ ___________

Health and Medical Technical Authority Date

____ ___________

Safety and Mission Assurance Technical Authority Date

____ ___________

Program/Project Manager Date

____ ___________

Chief Engineer/Lead System Engineer Date

____ ___________

Human Systems Integration Lead Date

By signing this document, signatories are certifying that the content herein is acceptable as direction for managing this effort and that they will ensure its implementation by those over whom they have authority.

Note: The intent of the following HSIP template is to provide guidance for new and experienced HSI Leads in the development of an HSIP and subsequent updates for project life-cycle milestones or necessary revisions due to major changes within the technical effort.

The template is designed to be used in the following way:

- *Black text indicates recommended text applicable to nearly every project. It can be tailored or used as-is in the early development of an HSIP.*
- *Blue italicized text indicates either instruction such as <Insert Program/Project name here> or provides text to guide the development of content for each section by providing examples or thought-provoking questions. This text allows complete flexibility for the HSI Lead to tailor the plan to meet the unique needs and scale of the assigned project.*
- *In Section 4 of the template, each HSI domain area contains a set of questions for consideration. The intent of these questions is to elicit domain specific content and to serve as primers to aid in the description of domain considerations. They are not intended to be answered within the HSIP.*
    - *Note that during the early stages of a project, the HSI Lead may determine that a question is not applicable for a specific project.*
    - *Relevancy of some questions in these lists may not be realized until later in the life cycle. It is suggested that with every update of the HSIP, the HSI Lead return to the template to review the domain specific questions for applicability and potential inclusion.*

TABLE OF CONTENTS

Executive Summary

This Human Systems Integration Plan (HSIP) summarizes the planned technical and managerial approach to implementing HSI for the *<Insert Program/Project name here>*, throughout its life cycle. The HSIP is the first step in the process of planning and executing the HSI effort to mitigate programmatic and technical risk and provide the mechanism to proactively identify and resolve potential issues before they impact program and mission success.

<Insert general system and mission description>

To meet the objectives of the *<Insert Program/Project name here>*, this HSIP identifies specific user, developer, and project office considerations to fully integrate human characteristics into the system design and functional elements. The purpose of the HSIP is to ensure human performance requirements are appropriately considered and incorporated into the user generated acquisition documents and into the contractor's system design. The HSIP will evolve and be updated throughout the project's life cycle and as driven by other significant system engineering project events, such as design reviews and/or milestone decisions. HSI issues associated with the development and fielding of the *<Insert Program/Project name here>* are identified, addressed, and tracked. Plan updates will coincide with *<Insert Program/Project name here>* technical evolution and will be used to assess/resolve HSI related issues.

The *<Insert Program/Project name here>* HSIP is structured to ensure all aspects of human involvement are integrated into the design of the *<Insert Program/Project name here>* system as a whole. It describes how the NASA HSI domains (see Figure A.1) are integrated and assessed, how HSI risks are identified, and how risk mitigation plans are developed and implemented throughout the *<Insert Program/Project name here>* life cycle. The HSI Lead, appointed by the Project Manager, is responsible for the development, implementation, and maintenance of this HSIP.

Figure A.1. NASA HSI Domains

This HSIP addresses the following:

- The planned strategy and approach for implementing HSI practices and processes across the project life cycle, either through leadership of activities or contributions to other technical efforts to ensure HSI principles are applied to each relevant project system and sub-systems.
- The HSI organizational structure including the personnel, location (government, contractor organization, or both), a summary of their qualifications, and the roles and responsibilities of the HSI Team within that structure.
- Roles and responsibilities for coordinating integrated HSI domain inputs with the Program/Project and any working groups, committees, or boards and stakeholders.
- HSI goals, activities, products, and deliverables for each phase of the project life cycle.
- Planned methods, tools, requirements, processes and standards for conducting HSI.
- Human-centered requirements derived from the ConOps and based on results of functional analyses performed during pre-Milestone A activities.
- Strategy for identifying, mitigating, and resolving HSI risks.
- Alignment strategy with the SEMP and the approach for integrating HSI into the SE processes, analyses, and activities.
- Alignment strategy with applicable Health and Medical and Safety and Mission Assurance policies or processes.
- Strategy for updating and maintaining the HSIP throughout the project life cycle.

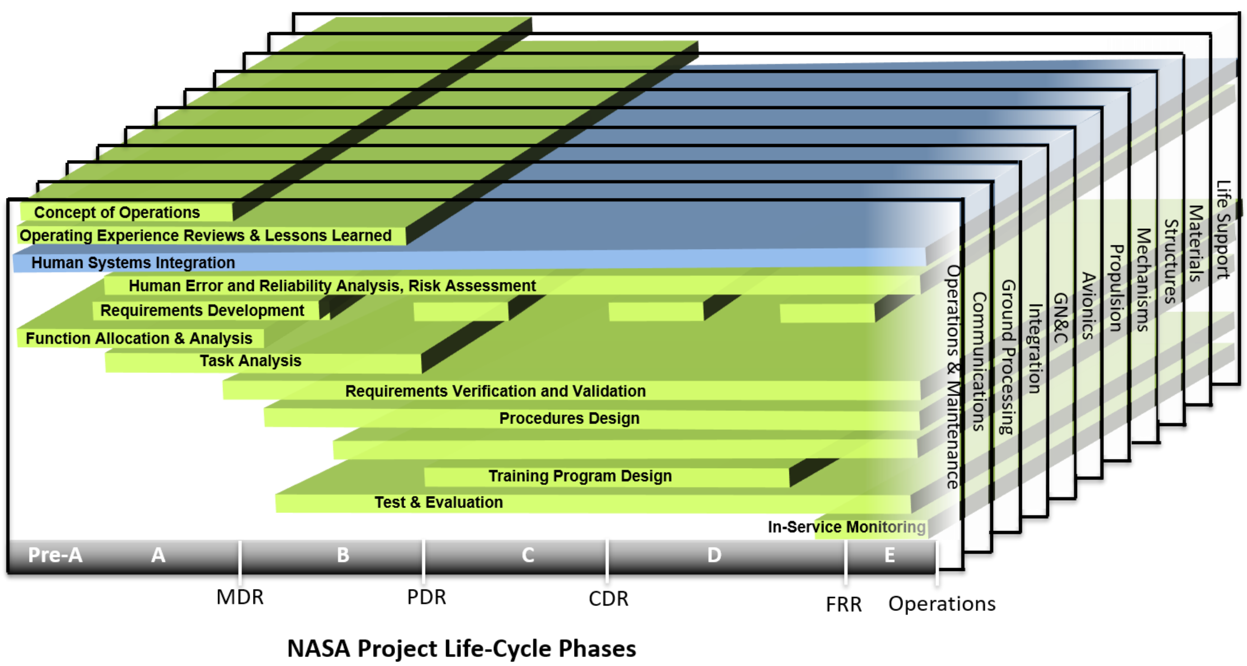

Figure A-2. HSI Activities Crosscut all Project Sub-Systems and Life-Cycle Phases

1.0 Introduction

The *<Insert Program/Project name here>* Human Systems Integration (HSI) Plan addresses implementation of HSI activities and products through the NASA systems engineering and project life-cycle processes to ensure the full integration of the human element with all other components of the system. The *<Insert Program/Project name here>* HSI effort described ensures the application and integration of all NASA HSI domains. This includes the *design, development, test, operation, and deployment efforts; including but not limited to those associated with safety and mission assurance, flight sciences, flight systems, operations, and ground support* aspects of the *Program/Project* life cycle.

1.1 Purpose

This HSIP describes and defines the processes and organizational roles and responsibilities for planning, executing, managing, and evaluating HSI processes and activities associated with the *<Insert Program/Project name here> development, testing, and fielding effort*. It documents the trade-offs and decisions made affecting the human elements of the system (to include operators, maintainers, assemblers, and test and support personnel). It is not intended for HSI processes to duplicate efforts that are the responsibility of systems engineering communities and project stakeholders, but to comprehensively and robustly integrate the human concerns of those stakeholders in balance with other project objectives. The intent is to create a deliberate means of accounting for the human as component of the total system solution utilizing an integrated methodology.

1.2 Scope

The HSIP provides HSI technical plans for the project, thereby serving as a communications bridge between the project management team and the HSI technical implementation team. The HSIP documents the planned systematic, integrated approach and specifies HSI processes that will ensure the *<Insert Program/Project name here>* system, its equipment, and its facilities:

- Incorporate effective human-centered design into systems interfaces
- Achieve required levels of human performance and system effectiveness
- Make economical demands upon resources, skills, and training
- Minimize total ownership costs
- Enable humans to mitigate and manage known failures and emergencies, as well as unexpected off-nominal events
- Identify, mitigate, and manage the risk of loss or injury to personnel, equipment, or the environment.

Ensuring HSI design compatibility will be accomplished through documentation, prototypes, acquisition documentation, and design reviews. The HSIP is the primary tool for outlining and documenting HSI efforts; establishing the preferred management approach and guidelines, and tracking and documenting HSI risks, risk mitigations, HSI requirement V&V. Additionally, the HSIP may serve as an audit trail that documents HSI data sources, analyses, activities, trade studies, and decisions not captured in other project documentation.

2.0 Relevant Documents

This section lists additional, related documents. Section 2.1 lists the applicable documents and Section 2.2 lists reference documents for information purposes.

This section should list all documents, references, and data sources that are invoked by HSI's implementation on the project, that have a direct impact on the HSI outcomes, and/or are impacted by the HSI effort. This section should list major standards and procedures that this technical effort for this specific project needs to follow. Examples are included in the table below and should be tailored for the project HSI needs. For additional applicable documents, refer to Appendix G, HSI Resources in the NASA HSI Handbook.

2.1 Applicable Documents

Table A-1 lists documents that are specifically called out in this document. The documents listed in this section are applicable to the extent specified herein.

Table A-1. List of Applicable Documents

Document Number	Document Title
	Project Management Plan (PMP)
	Systems Engineering Management Plan (SEMP)
	Risk Management Plan (RMP)
	Concept of Operations (ConOps)
	Verification and Validation Plan (VVP)
	System Requirements Document (SRD)
NPR 7123.1	*NASA Systems Engineering Processes and Requirements*
NPR 7120.5	*NASA Space Flight Program and Project Management Requirements*
NPR 7120.8	*NASA Research and Technology Program and Project Management Requirements*
NPR 8705.2	*Human Rating Requirements for Space Systems*
NASA/SP-20210010952	*NASA HSI Handbook*
NPD 8720.1	*Reliability and Maintainability Program Policy*
NPD 7100.8	*Protection of Human Subjects*
NASA-STD-3001 Vols 1 & 2	*NASA Spaceflight Human-System Standard*
SAE-6906	*Standard Practice for Human Systems Integration*
NUREG-0711	*Human Factors Engineering Review Model*
HF-STD-001	*FAA Human Factors Design Standard*

2.2 Reference Documents

Table A-2 lists documents that contain supplemental information in the application of this document. The documents listed in this section are expected to be applicable to the extent specified herein.

Table A-2. List of Reference Documents

Document Number	Document Title
	System Integration Test Plan
	Flight Test Plan
	Risk Management Plan (RMP)
	Safety and Mission Assurance Plan (SMAP)
	System Safety Plan
	Software Management Plan (SMP)
	Maintenance Plan
	Operations Nomenclature Plan

3.0 HSI Strategy

This section summarizes the HSI management, planning, approaches, and strategies for the *<Insert Program/Project name here>* which will be implemented throughout the project life cycle. It describes how HSI products will be integrated across all HSI domains and how HSI inputs and activities contribute to system performance.

Per the *NASA/SP-20210010952,* NASA HSI Handbook, the key to a successful HSI strategy is dependent on the comprehensive integration and collaboration of HSI products and processes across all HSI domains, as well as, other core acquisition and engineering processes. Additionally, HSI domain process integration should include integration with the project's SE technical management processes and project technical processes with the goal of positively impacting system performance and LCC.

Robust HSI efforts early in the project life cycle will drive HSI requirements development, provide an accurate representation of human performance, prevent redesign, potentially increase system performance, reduce LCCs, and mitigate risk. This ensures that the system accommodates the capabilities and limitations of the humans—both at the overall system level and at the individual subsystem and component levels. Furthermore, the HSI strategy will ensure that the HSI requirements are accurately defined, verified with appropriate methodology and success criteria, and the products validated through developmental test and evaluation activities.

Describe how the requirements drive the HSI effort and the strategy for verifying and validating these requirements. Specifically, address traceability from high-order requirements to performance specifications.

The HSI strategy will include:

- Data sources and availability, including
    - applicable research,
    - predecessor system(s), and
    - risk analyses.
- HSI constraints, including
    - those imposed on system acquisition/technology development, and
    - those imposed on the HSI program or level of effort.
- Approaches and planning, including
    - how HSI products will be integrated across all HSI domains and mapped to project focus areas,
    - how HSI inputs to SE and management processes contribute to system performance and help contain LCC,
    - alignment with the Systems Engineering Management Plan and other control documents, and
    - a schedule of key HSI milestones.

3.1 HSI Program Roles and Responsibilities

This section defines the processes and organizational roles and responsibilities for planning, managing, executing, controlling, and evaluating the HSI activities associated with the Project. The HSI Lead and Team are responsible for providing integrated HSI input, in conjunction with program management and systems engineering, and are responsible for implementing HSI processes throughout the *<Insert Program/Project name here>* life cycle. The HSI Team's roles and responsibilities, not only within the HSI team, but also for the HSI team's overall interaction with the larger program management and SE teams, with other hardware/software discipline teams, and with technical authorities, are clearly defined in this section. Another responsibility of the HSI Team is to identify, resolve, and track HSI activities as *<Insert Program/Project name here>* progresses. These activities are integrated into the defined project processes and interfaced through Integrated Product Teams (IPTs) and/or working groups (WGs), T&E activities, and risk management. HSI Team responsibilities for *<Insert Program/Project name here>* include, but are not limited to, the following tasks:

NOTE: This section should describe the defined authority, responsibility, and accountability of the HSI Lead and HSI Team (if applicable). Additionally, the following list provides a description of HSI responsibilities. This list should be tailored to meet the set of those that have been mutually agreed to by the HSI Lead and the PM.

- *Develop HSI-related contractor requirements through the RFP and SOW*
- *Includes identification of HSI products and deliverables (e.g., HSIP, developmental test plans) and ensuring that appropriate contract clauses and data requirement descriptions are included.*
- *Collaborate with the Lead Systems Engineer*
- *Develop a plan for integrating HSI processes into the systems engineering process.*
- *Provide inputs during the development of the ConOps*
- *Ensure the ConOps considers all personnel required for operating, maintaining, and supplying the system.*
- *Ensure the ConOps includes descriptions of all human interactions with the system during all operational phases, required skill sets and training needs.*
- *Develop and manage HSI requirements across all project disciplines.*
- *Evaluate, operations, systems and subsystems for identification of HSI requirements.*

- *Ensure that HSI SMEs are employed to develop all HSI requirements and ensure these requirements are incorporated into pertinent life-cycle documents.*
- *Develop requirement descriptions ("shall" statement) and rationale.*
- *Collaborate and iterate with systems and subsystems teams; ensure HSI requirements are understood and effectively implemented.*
- *Develop a plan for HSI requirements V&V.*
- *Develop the verification description, methodology, and success criteria for each HSI requirement.*
- *Participate in program analysis and requirement verification cycles.*
- *Participate in Technical and Design Reviews.*
- *Influence system design by identifying HSI constraints and risks.*
- *Propose design solutions, risk resolution, courses of action, and/or risk mitigation actions.*
- *Provide and/or verify the adequacy of HSI input as identified in system specification and other acquisition documents.*
- *Participate in IPT and WG activities to include teams addressing Human Rating, Certification and Airworthiness, Systems Engineering, Logistics, System Safety, Integration and Test, Operations, Crew Systems, and Training:*
- *Participate in system/sub-system design, review, and planning to ensure relevant HSI considerations are appropriately accommodated for in the design of systems, sub-systems, and the integration of systems (total system of systems).*
- *Participate in test planning and analyses to ensure HSI issues have been sufficiently incorporated in test requirements, test procedures, test safety requirements, success criteria, operations documents, and training plans.*
- *Participate in the implementation of HSI by performing analyses, studies, investigations and inspections throughout the life cycle of the program.*
- *Advocate for implementation of corrective action to address HSI shortfalls.*
- *Maintain a database for the HSI team or working group on a shared portal. This tool will serve an audit trail and ensure HSI activities and concerns are documented and tracked to resolution.*
- *Support HSI team or working group Technical Interchange Meetings (TIMs) and other working groups as appropriate for HSI matters.*
- *Lead the HSI Team and Working Group*

3.2 HSI Team Organization

This section should contain a description of the HSI team organization, with emphasis on how HSI should be a key consideration during the formation of IPTs/WGs, and how representatives from the HSI domains should be active IPT or WG members. This section could contain a description of the personnel qualifications for who will be implementing HSI for the project. The HSIP should describe the HSI organization and identify its leaders and membership. It should describe the organizational structure of the overall program/project (including industry partners) and the roles and responsibilities of the HSI team within that structure as well as reporting structure (see the NASA HSI Handbook, Section 5.1 for example organizational structures with HSI). The HSIP should detail the HSI team's relationship to other teams, including those for systems engineering, logistics, risk management, test, verification, and operations. Define how collaboration will be performed among the HSI Lead, HSI team, and IPTs and Working Groups directed at other programmatic areas.

3.2.1 Technical Forums

The *<Insert Program/Project name here>* has established technical forums to facilitate cross-discipline integration, communication, and collaboration. The HSI Lead and Team will collaborate with the project Integrated Product Teams (IPTs) and Working Groups (WGs), as well as with relevant institutional organizations where HSI domain SMEs are likely located. To provide a forum for integrating across the various disciplines of HSI, the *<Insert Program/Project name here>* will maintain an HSI WG which will include participation from SME's and stakeholders within the project IPTs and WGs. This integrated structure will enable the HSI Team to efficiently and effectively implement HSI domains across the various project disciplines.

The HSI Lead and Team will participate and collaborate with the below list of *<Insert Program/Project name here>* Working Groups:

The following are some examples of what should be considered here. For each, provide a project specific description and include the scope of the WG, who it's led by (Chief Engineer, Systems Engineer, etc.) and indicate appropriate contractor counterparts if applicable:

- *Certification / Airworthiness Working Group*
- *Systems Engineering Working Group (SEWG)*
- *System Safety Working Group (SSWG)*
- *Integration & Test Working Group*
- *Flight Test Operations Working Group*
- *Cockpit Pilot Vehicle Interface (PVI) Working Group*

The HSI Lead and Team will participate and collaborate with the below list of *<Insert Program/Project name here>* Integrated Product Teams (IPTs) which will focus on the development of the associated products and systems.

The following are some examples of what should be considered here. For each, provide a project specific description and include the scope of the IPT, who it's led by and indicate appropriate contractor counterparts and support personnel, if applicable:

- *Air Vehicle IPT*
- *Performance and Simulation IPT*
- *Test and Evaluation IPT*
- *Logistics IPT*
- *Software IPT*
- *Crew Systems IPT*
- *Production IPT*

4.0 HSI Domains

Successful and effective implementation of HSI depends on the integration and collaboration of all the NASA HSI Domains described below. Each domain has the potential to affect and interact with the other domains, making it critical to execute an integrated approach. Additionally, decisions, changes, environmental disturbances, or new system constraints introduced into one domain will disturb the balance of interdependencies between the domains and potentially impact one or more of the other domains. For HSI to optimize total system performance (i.e., human + hardware + software), the appropriate HSI domains should be engaged throughout the system life cycle.

This section identifies the HSI domains applicable to *<Insert Program/Project name here>* including rationale for their relevance. Additionally, this section describes the HSI issues that involve potential technical, cost or schedule risks.

4.1 Human Factors Engineering

For the *<Insert Program/Project name here>*, the HFE effort will be applied to the following three interrelated areas of system development: 1) analysis, 2) design and development, and 3) test and evaluation of the system hardware, software and associated user interfaces, procedures, and facilities. Additionally, the HFE effort will be integrated with the larger system engineering efforts and with activities in other HSI domains.

To achieve efficient, effective, and safe human-system performance across all systems, equipment, and the associated human tasks and activities, the *<Insert Program/Project name here>* will be designed and developed with focus on the integration and accommodation of human performance characteristics (both cognitive and physical). To define the parameters and constraints that influence human performance, HFE draws upon applied research in several complementary disciplines including, but not be limited to: psychology, ergonomics, kinesiology, engineering, medicine, biomechanics, anthropometry, anthropology, sociology, and physiology.

The HFE approach for development of specific requirements will likely vary based on roles assumed by specific members of the target audience. This section should contain a high-level description of the HFE design elements of the project followed by specific design considerations. Below is a short list of industry recognized design considerations that are informed by engineering standards, handbooks and observed best practices from legacy systems that may or may not be applicable to the project.

- *Airworthiness certification requirements (e.g., safety and emergency egress provisions) will influence HFE design considerations.*
- *Anthropometric accommodation requirements will have a direct impact on design considerations.*
- *Human factors specialists will assess workload; all interfaces; and optimize ergonomics for the human. Workload will be assessed to ensure the resulting workload does not exceed trained personnel's abilities or jeopardize mission safety or completion.*
- *Teaming, both human-human and human-machine and their effects on system behavior and performance are considered in system design.*
- *Excessive workload demands (stress/mental effort/time constraints) shall be accommodated/minimized under extreme environments (assembly, integration, test, and operational conditions), and high workload tasks/procedures.*
- *Operators will be provided with high-level indicators to alert them to real-world status changes and permit selection of multiple levels of detailed data for the appropriate real-time problem-solving capability. Operational status and capability of hardware and hardware interfaces are reported in such a way to be clearly evident to the operator.*
- *Real-time operation of the system (e.g., issues related to safety of flight) will be ensured. Any manual actions not appropriate at a certain operational level shall be designed out, or if not feasible, provide for an appropriate level of operator intervention (override capability). This would prevent accidental or irrational intervention that might result in safety degradation or other major errors.*
- *Built-in maintenance displays should be clear and easily usable by the operators and maintainers.*
- *Systems capabilities will be ergonomically designed to lessen user's stress and fatigue.*

- *Software reliability will be verified through use of a real-time verification system or analytical tool to demonstrate software is operating properly (e.g., real-time error control should have positive and negative responses). The software should indicate whether it is cycling properly and if all interfaces are established.*
- *Through the course of systems development, system interface modifications should be documented and monitored for possible impacts to future interfaces.*
- *Design requirements should be defined to account for HSI considerations for development, assembly, integration, and test personnel.*
- *HSI considerations for maintainability should include: Fault detection and isolation for all associated equipment and maintenance procedures. To greatest extent possible, system will be designed for optimal accessibility and clearance; to support future modifications.*
- *With respect to on-going system support, sustainment tasks, workload, access, occupational health, skills, training, and hazards can be impacted by technology incorporated and should be reviewed for HSI implications.*
- *To support testing and evaluation, suitability, usability, workload levels, operability and maintainability should be verified as early as possible through appropriate analysis, demonstration, inspection, developmental and operational testing.*

To provide additional detail or clarification of what may be intended by the above design considerations or to aid in development of additional design considerations, provided below is an extensive, yet not exhaustive, list of HFE related questions that may be helpful when developing, or especially when updating, this section. These are not intended to be answered within the HSIP but should serve as primers to aid in the description of design considerations:

- *Will/Does the design require a new system interface or modification to an existing interface?*
- *How might/does the design require collaboration between humans and/or across systems?*
- *Does the design account for personnel occupational health and safety considerations in both nominal and off-nominal conditions?*
- *Will/Does the design account for ease of access for development, assembly, integration, maintenance, and test personnel?*
- *Should/Will lighting conditions and their effect on operations be a factor in design?*
- *Is there special gear, or technology, required that may impact task performance?*
- *Will there be physical issues (anthropometry, etc.) that may impact the design of the system interface?*
- *Will new technology impact the interface or system behavior (automation, aiding)?*
- *Does the design require the performance of additional tasks from what was anticipated?*
- *Can specific performance thresholds and objectives be identified that impact mission outcome?*
- *Will there be/Are there time limitations for task accomplishment?*
- *Will there be/Are there accuracy requirements for task accomplishment?*
- *Will/Are the alarms displayed by priority?*
- *Will/Are critical safety alarms easily distinguishable from control alarms?*
- *Will there be/Is an alarm summary permanently on display?*
- *Does the design account for nuisance alarms to be corrected and redundant alarms eliminated as soon as practical to help prevent complacency toward alarms?*
- *What are the physical constraints and workload placed on the operator/crewmember by the system?*

- *What are the cognitive constraints and workload placed on the operator/crewmember by the system?*
- *What is the system's ability to minimize the effect of environmental stressors on the operator/crewmember?*
- *What is the system's ability to minimize the effect of mechanical stressors on the operator/crewmember?*
- *What is the system's compatibility with human life support and continuous operations?*
- *Do the displays provide an adequate view of the entire process as well as essential details of individual systems?*
- *Are the number and frequency of manual adjustments required during normal and emergency operations limited so that operators can make the adjustments without a significant chance of mistakes as a result of overwork or stress?*
- *Does the system design minimize risk of occupational hazards during routine and emergency performance of job functions?*

4.2 Operations

Operations includes designing systems to enable robust, cost-effective operations for human effectiveness and mission success. It involves consideration of lessons learned from past operations in other programs in conjunction with mission objectives for the current program, in the development of concepts of operations (ConOps), procedures, functional allocation, and crew resource management.

Discuss how lessons learned from operations of past programs are being leveraged for this program. Discuss how human performance characteristics are being taken into consideration for procedure development. What operator skills or other factors are at play, and how does this feed into functional allocation of roles and responsibilities, teaming, human-automation-robotic integration, and more. Provided below is an extensive, yet not exhaustive, list of Operations related questions that may be helpful when developing, or especially when updating, this section. As before, the intent is not to answer the questions within the HSIP but that these should serve as primers to aid in the description of the operational considerations:

- *Have personnel resources been justified and/or modified to meet mission needs? How much could personnel grow before it would impact the life-cycle cost (LCC) decision?*
- *Is there a desire and/or need for unique combinations of skill sets, knowledge bases, and abilities?*
- *Are the required skill sets, knowledge base, and abilities projected to be available in the timeframe required? If not, will training be sufficient or will system design or operation need to be modified?*
- *Is the control room always occupied (i.e., assigned duties do not require the control room operator to be absent from the control room)?*
- *Have the effects of shift duration and rotation been considered in establishing workloads? Is the number of extra hours an operator must work if his or her relief fails to show up sufficiently limited so that the operator safety is not adversely affected?*
- *Have differences in gender mix and/or cognitive abilities, physical characteristics, psychomotor skills, and/or experience level been taken into account in the design?*
- *Does the design take into account the projected user (operators, assemblers, testers, and maintainers) community?*
- *Is decision making being trained and assessed as part of readiness level assessment?*
- *Have lessons learned from previous programs been assessed in relation to the system objectives?*
- *Is there a peer review of procedures and checklists before starting a project, shift, or mission?*

- *Is it clear in procedures whether sequence of steps matters or can they be done in any order?*
- *How will out of sequence workflow steps be tracked and documented?*
- *Are commands sent out of procedure verified visually by a second operator to ensure no misspellings, misunderstandings, mishaps occur?*
- *Are more experienced personnel being paired with incoming or new personnel? Are both groups open to suggestions (two-way feedback)? If no pairing exists, does a mentoring program need to be developed?*
- *Is visual and verbal confirmation re-enforced? (Communication can be broken due to various noises on testing area, console, or on the loops, which may result in misunderstandings for next steps.)*
- *Are operations costs assessed early in the design phase of the mission life cycle?*
- *Have total system operational performance, support, or LCC objectives and thresholds been defined?*
- *Are automatic safety features provided when a process upset may be difficult to diagnose due to complicated processing of various information?*
- *Have charts, tables, or graphs been provided (or programmed into the computer) to reduce the need for operators to perform calculations as part of the operation? If operators are required to perform calculations, are critical calculations independently checked?*
- *Are the number and frequency of manual adjustments required during normal and emergency operations limited so that personnel (users, assemblers, maintainers, etc.) can make the adjustments without a significant chance of mistakes because of overwork or stress?*
- *Does the system ensure that values manually entered are within a valid range?*
- *Do written procedures exist for all operating phases (i.e., normal operations, temporary operations, emergency shutdown, emergency operation, normal shutdown, and startup following a turnaround or after an emergency shutdown)?*
- *Are safe operating limits documented, providing consequences of deviating from limits and actions to take when deviations occur?*

4.3 Maintainability and Supportability

Maintainability and Supportability, includes a strong relationship to the Reliability and Maintainability (R&M) and Safety domains, addresses design, development, and execution of simplified maintenance and optimization of resources, spares, consumables, and logistics given corresponding mission constraints and objectives.

Provided below is an extensive, yet not exhaustive, list of Maintainability and Supportability related questions that may be helpful when developing, or especially when updating, this section. As before, the intent is not to answer the questions within the HSIP but that these should serve as primers to aid in the description of the Maintainability and Supportability considerations:

Simplified maintenance and reliability and maintainability considerations would address questions like:

- *a. Are maintenance interval goals identified?*
- *b. Is the expected maintenance time compared to reliability estimates to identify possible areas of risk?*
- *c. Are the ease and time for installations or removals of equipment considered in the design?*
- *d. Has responsibility for maintaining and updating labels been assigned?*

Similarly, Safety considerations would address questions like:

- *a. Has using interchangeable parts been considered, if they would increase operational flexibility or contingency response options without causing hazards?*

b. Are hazards identified for design requirements and solutions that are exposed during assembly, integration, test, and/or maintenance activities?

c. What are the methods considered to eliminate such hazards or protect from hazards?

d. Are adequate barriers erected to limit access to maintenance, cleanup, or critical work site areas?

Finally, Maintenance and Supportability resource optimization would address questions like:

a. Approximately how many resources will it take to assemble, integrate, test, operate, maintain, train and support the system?

b. What personnel estimate was used for the LCC assessment?

c. How does the personnel estimate compare to current requirements?

d. Will significantly new skill sets, knowledge bases, and abilities be required to support the capability?

e. Is personnel time for productive activities being addressed during design to conduct preventative and corrective maintenance activities?

f. Have hazardous maintenance or supportability operations been identified for the system?

4.4 Habitability and Environment

The Habitability and Environment domain focuses on designing with consideration for internal/external environments and the impacts to human morale, safety, health, and human/mission performance.

Numerous technical resources and areas of expertise directly relate to habitability and the environment, including:

- Environmental and Occupational Health
- Radiation Health
- Toxicology
- Nutrition
- Acoustics
- Architecture
- Health and Countermeasures
- Physiology
- Medical Concerns
- Lighting

This section of the HSIP should discuss how each of these areas of expertise will be included in the HSI implementation for this project. Indicate meetings, working groups, TIMS, control boards, and integration forums to which each of these will be invited, how they will be engaged (for example when engaged by special topic or area of concern, to a meeting or working group or control board that they do not regularly attend). Discuss which requirements for the program are of particular interest to these technical areas of expertise, and who (by role if not by name) will be used to represent and work through mitigations for issues as needed. Provided below is an extensive, yet not exhaustive, list of Habitability and Environment related questions that may be helpful when developing, or especially when updating, this section. As before, the intent is not to answer the questions within the HSIP, but that these should serve as primers to aid in the description of the Habitability and Environmental considerations:

Acoustical Energy

- *What are the noise levels for the system? Can they be reduced? What are the concerns for potential assembly, integration, test, maintenance, and operational locations? Is noise maintained at a tolerable level?*
- *Does this system meet the standards for steady state noise under the most severe scenarios?*
- *Does this system meet the standards for impulse noise under the most severe scenarios?*
- *Are alarms audible above background noise?*

Lighting

- *What are lighting requirements for the system under all conditions?*
- *Can the lighting system accommodate individual performance differences?*

Biological Substances

- *Does the system configuration preclude exposure to microorganisms, their toxins and enzymes?*

Chemical Substances

- *Does this system produce or release any toxic substance during assembly, integration, test, maintenance and operation?*
- *Could personnel be exposed to unacceptable levels of toxic vapors, gases, or fumes?*
- *Could there be any unacceptable levels of toxic gases?*
- *Has each chemical or toxic material used in or with the system been identified in the health hazard assessment report?*
- *Does a hazard from/exposure to any chemical substance exist?*

Radiation Energy

- *Are there hazards or potential hazardous exposures from ionizing radiation sources during operation, training, and maintenance?*
- *Are there hazards or potential hazardous exposures from non-ionizing sources during operation, training, and maintenance?*
- *Does the system contain any lasers detrimental to health?*
- *Will the system be evaluated for potential radiation health hazards?*
- *Will the system be designed with protection systems to ensure that radiation exposure is kept as low as reasonably achievable?*

Physical Forces

- *Will this system produce any physical hazards?*
- *Is adequate protection provided to preclude trauma to the eyes or body surface during system interaction?*
- *Does the system meet vibration and shock requirements under all operational conditions (nominal and contingency scenarios)?*

Survivability

- *Will the proposed capability increase the number/type of individuals placed in harm's way?*
- *Does the concept design change egress systems requirements (if applicable)?*
- *Does the Concept of Operations (ConOps) for the proposed capability increase the need for improved personnel survivability features?*

- *Is the general environment conducive to safe job performance?*

Temperature

- *Does the system provide adequate heating, cooling, and ventilation under routine, severe, and emergency conditions?*

Medical

- *Have health problems identified with legacy/reference systems and components been addressed and abated in this system?*
- *What are disposal requirements? Will this process generate waste with special handling/disposal requirements?*
- *If waste cannot be eliminated, then will there be additional training requirements for use, handling, storage and disposal?*
- *Does the system exhibit unacceptable conditions that might affect human performance capabilities (i.e., vision, olfaction, taste, hearing, reaction time, motor skills, strength, and cognitive skills)?*
- *Have required health services (i.e., nutrition, water, sleep, exercise, medical care [preventive, diagnostic, treatment]) been identified where applicable?*
- *Have required living conditions (i.e., personal hygiene, body waste management, crew quarters, mess, exercise area, recreation, trash, stowage, etc.) been identified where applicable?*

4.5 Safety

The Safety domain focuses on designing with safety factors and hazard controls to minimize/mitigate risk to personnel and mission.

Safety considerations should include some of the following areas of expertise:

- Safety analysis
- Human error analysis
- Reliability
- Quality Assurance
- Factors of survivability
- Human rating
- Hazard analysis

The HSIP should describe when in the life cycle task analyses, safety analyses, human error analyses, reliability analyses, and hazard analyses will occur, as well as who are the responsible parties to perform these analyses. The plan should also describe how these analyses will be documented, which program deliverables will include them, and how they will be used to drive reduction of risk or to mitigate potential design issues. Provided below is an extensive, yet not exhaustive, list of Safety related questions that may be helpful when developing, or especially when updating, this section. As before, the intent is not to answer the questions within the HSIP but that these should serve as primers to aid in the description of the Safety considerations.

- *Is a safety risk assessment needed?*
- *Have safety risks concerning power sources been considered?*
    - *Electrical*
    - *Mechanical*
    - *Hydraulics/pneumatics*

    - *Chemical/explosive/propellants*
- *Have safety risks associated with the following been considered?*
    - *Exposed, moving equipment*
    - *Hazardous materials or by-products*
    - *High temperature devices*
    - *Vehicular movement/flight*
- *Have the design requirement statements been developed to address/prevent the impact of the following?*
    - *Catastrophic loss of system or personnel due to failure/malfunction of component or procedural error/omission*
    - *Operational loss of system or disabling injury due to failure/malfunction of component or procedural error/omission*
    - *Loss of system effectiveness or injury due to failure/malfunction of component or procedural error/omission*
- *Are all trade-offs or impact issues looked at for their effects on all other HSI domains as well as system cost and performance requirements (e.g., excessive training and personnel capability requirements to compensate for system design weaknesses)?*
- *Are all functional, cost and performance data, as well as assumptions and other criteria, consistent with other analyses being performed on the system?*
- *Is the system safe for personnel to operate, assemble, maintain, integrate, repair, test, and support?*
- *Does the system account for personnel occupational health and safety considerations under all conditions?*
- *Are nominal and emergency lighting sufficient for all area operations? Is there adequate backup power for emergency lighting?*
- *Are adequate supplies of protective gear readily available for routine and emergency use?*
- *Are personnel able to perform both routine and emergency tasks safely while wearing protective equipment?*
- *Is emergency equipment accessible without presenting further hazards to personnel?*
- *Can operators safely intervene in computer-controlled processes? Do operators believe that the control logic and interlocks are adequate?*
- *Does a dedicated emergency shutdown mechanism exist? If so, is it in an appropriate location?*
- *Is the number of manual adjustments during normal operations sufficient to avoid mistakes as a result of boredom?*
- *Do procedures address the personal protective equipment required when performing routine and/or non-routine tasks?*
- *Are all personnel trained to report near misses for incident investigation program?*

4.6 Training

The Training domain focuses on designing to account for ease and reduction of time needed to develop and provide effective training and the resources to maximize human retention, proficiency, and effectiveness to successfully accomplish tasks and mission. The *<Insert Program/Project name here>* training program will be designed to simplify the resources that are required to provide personnel with requisite knowledge, skills, and abilities to properly operate, maintain, support the system, and meet mission requirements. This section will describe how the program will establish a system and framework for providing high quality training for all relevant mission personnel.

This section should describe how the Program/Project has an established system and framework for providing high quality training for all relevant mission personnel.

For example, does the system require specialized skills, unique methods, or repeated training sessions? Often training plans are only considered after designs have been completed and are fixed. Considering training during earlier concept phases would make training more effective, as well as would ensure that designs selected during trade studies have been evaluated to assess their impact on training. The HSIP documentation of the training approach should address training concepts and strategy in areas appropriate to the system. Training areas such as equipment familiarity, facilities, simulations, training aids, use of virtual systems, required skills, task time constraints, and system access constraints are likely to apply. Provided below is an extensive, yet not exhaustive, list of Training related questions that may be helpful when developing, or especially when updating, this section. As before, the intent is not to answer the questions within the HSIP but that these should serve as primers to aid in the description of the Training considerations:

- *Is the system reliable enough that training alone is not a single point of failure?*
- *Are designs selected during trade studies evaluated to assess their impact on training?*
- *Is the design accounting for ease and reduction of personnel time needed to provide training to both operators and maintainers?*
- *Are training methods and materials being developed efficiently to maximize human acquisition, retention, retrieval, and transfer?*
- *Are training facilities and equipment being prepared efficiently to maximize human retention, proficiency, and effectiveness?*
- *Is any part of the planned system functionality related to addressing human performance or training deficiencies?*
- *Could temporary or interim training be implemented to improve mission performance with current systems until the proposed design can be developed and deployed?*
- *Will deployment of a new capability change personnel planning and decision-making? If so, will changes in either individual or team training be required?*
- *Will the operator/crew be tested for preliminary workload estimates in visual, auditory, motor, and cognitive capacity? Do they meet requirements?*
- *If there is a desire and/or need for unique combinations of skills, knowledge, and abilities, are associated new training requirements feasible and reasonable?*
- *Will there be sufficient time to adjust and implement required changes to training?*
- *Will the design change who is to conduct the training (Government, Contractor)?*
- *Will the design change where the training is conducted (Contractor Facilities, NASA Centers)?*
- *Will the design impact the timing of the training (duration, availability)?*
- *Will training needs, development, and implementation affect cost estimates and LCC assessments?*
- *Will the design change the method of training used (classroom, computer-based, on-the job)?*
- *Do operators receive adequate training in safely performing their assigned tasks before they are allowed to work without direct supervision?*
- *Do operators practice emergency response while wearing emergency protective equipment?*
- *Do operators practice emergency response during extreme environmental conditions?*

- *Does a periodic refresher training program exist or will it be required? Is special or refresher training provided in preparation for an infrequently performed operation?*
- *When changes are made, are operators trained in the new operation, including an explanation of why the change was made and how operator safety can be affected by the change?*
- *Are assembly, integration, maintenance, and test personnel properly trained and have all required certifications to interact with the system?*

5.0 HSI Implementation

This section summarizes the HSI implementation approach and describes how the HSI strategy will be implemented throughout the project life cycle, i.e., description of activities, tools, and products planned to ensure HSI objectives are met; application of technology in the achievement of HSI objectives; and an HSI risk processing strategy that identifies and mitigates technical and schedule concerns when they first arise.

HSI is a continuous process that is applied iteratively. The *<Insert Project Name here>,* through the HSI Lead, will complete HSI assessments, studies and analyses, participate in the execution of system-level HSI activities, and document project office activities in support of the system-level HSI efforts. To facilitate accomplishment of project objectives HSI will actively engage with IPTs, working groups, test panels, and other project related teams to address HSI issues, concerns, and integration topics.

Typically, the HSI Lead works with the contractor HSI Lead/POC and will report to the Lead Systems Engineer or PM (See HSI Handbook Section 5.1). The HSI Lead will be responsible for maintaining the HSIP, and for coordination and communication of HSI activities and actions. The systems engineering team will work with the HSI Lead to integrate the Plan within the systems engineering process. The Lead Systems Engineer will also ensure that HSI SMEs are employed to develop HSI requirements and ensure these requirements are incorporated into pertinent project documents.

Topics to consider when writing this section:

- *Plan for developing and assessing HSI domain-specific and cross-domain HSI issues.*
- *Plan for HSI team involvement in ConOps development and update.*
- *Development of HSI requirements and trade-off analyses.*
- *Identification of the technical and programmatic tasks necessary in general and to resolve HSI related issues prior to each milestone review.*
- *How HSI will be applied to hardware, software, and architecture design and development.*
- *Identification of the HSI efforts that will be performed by the Government, Contractors, and/or partners, specifying the roles for each and how the efforts will be managed and integrated.*
- *Consider the creation and maintenance of an HSI issues log to track and resolve issues and concerns during the project life cycle.*
- *Identify HSI-related dependencies on other systems.*
- *Specify whether an HSI team or working group will be formed. If so, the team composition and function should be described.*
- *Specify other project teams that the HSI Lead/team will participate in and identify any unique HSI personnel roles.*
- *Specify all HSI related products to be developed, along with analyses and testing to be performed or supported.*
- *Describe how HSI V&V efforts will be accomplished.*

The HSI Lead engages in all project phases, including participation in project reviews (e.g., CDR) to conduct HSI activities, develop HSI products, collaborate with subject matter expertise for specific tasks across the project disciplines, and support the entire life cycle of the *<Insert Project Name here>.* The HSI Lead develops various HSI products from the onset of the project which will guide the execution of the approach. This comprehensive approach ensures that HSI is an integral component of project technical and management activities.

5.1 HSI Project Focus Areas

The following HSI Focus Areas have been identified as particular areas of focus for the project. HSI issues will be monitored and addressed for these areas as non-compliance/non-conformance could conceivably generate significant overarching program risk (major schedule shifts, cost variance or technical/performance concerns). While exhibiting some degree of overlap, these focus areas, map directly to HSI domains. HSI objectives will be derived from the focus areas and translated into domain-specific HSI planning actions and activities.

Figure A-3 captures the key *<Insert Program/Project name here>* HSI focus areas and may be modified as the program progresses through design, development, testing and fielding. Figure A-4 depicts project focus areas mapped to the HSI domains. *<Insert Program/Project focus areas>*

The following figures provide example project specific focus areas and suggestions of how to graphically depict project specific information in this section of the HSIP.

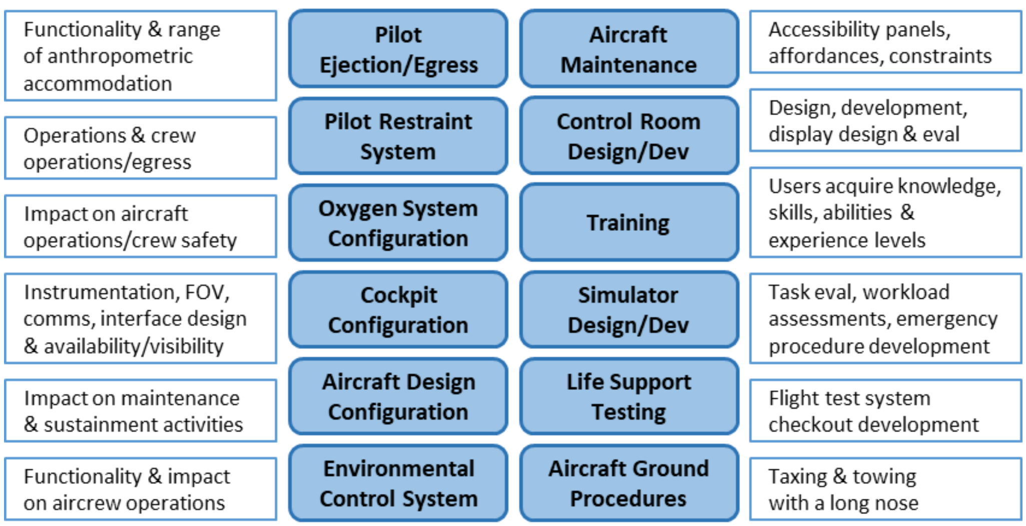

Figure A-3. Example HSI Focus Areas

Human Factors Engineering	Training	Maintainability and Supportability	Habitability and Environment	Safety	Operations
Pilot Ejection/Egress	Pilot Ejection/Egress			Pilot Ejection/Egress	
Pilot Restraint System				Pilot Restraint System	
Cockpit Configuration	Cockpit Configuration		Cockpit Configuration	Cockpit Configuration	
Aircraft Design Configuration	Aircraft Design Configuration			Aircraft Design Configuration	Aircraft Design Configuration
Life Support System	Life Support System		Life Support System	Life Support System	
Aircraft Maintenance	Aircraft Maintenance	Aircraft Maintenance	Aircraft Maintenance	Aircraft Maintenance	Aircraft Maintenance
	Aircraft Ground Procedures	Aircraft Ground Procedures		Aircraft Ground Procedures	Aircraft Ground Procedures
Control Room Design	Control Room Design			Control Room Design	Control Room Design
Simulator Design/Dev	Simulator Design/Dev			Simulator Design/Dev	
	Environmental Control System		Environmental Control System	Environmental Control System	
	Flight Test			Flight Test	Flight Test

Figure A-4. Example HSI Focus Areas Mapped to HSI Domains

5.2 HSI Issue and Risk Processing

This section describes the HSI-unique processes for identifying and mitigating human system risks. HSI risks should be processed in the same manner as other project risks (technical, cost, schedule). However, human system risks may only be recognized by HSI domain and integration experts. An important role of the HSI Lead is ensuring that risks to the human are identified and documented appropriately. It is also important to document any unique procedures by which the project identifies, validates, prioritizes, and tracks the status of HSI-specific risks through the risk management system. Management of HSI risks is the responsibility of the HSI Lead in coordination with overall project risk management.

It is important to note that while HSI may or may not 'own' risks within a Program or Project, risk tracking and management is an essential HSI function. This section should describe the following, at a minimum:

- Describe the negotiated HSI role with the Project Manager in identifying and managing risk in this section along with any unique processes that will be applied.
- How potential cost, schedule, technical risk, and trade-off concerns with the integration of human elements (operators, maintainers, ground controllers, etc.) with the total system are identified and managed.

- How HSI issues and any safety, health, or survivability concerns that arise as the system design and implementation emerge will be identified, tracked, and managed.
- Identify and describe any risks created by limitations on the overall project HSI effort (assumptions, time, funding, insufficient availability of information, availability of expertise, etc.).
- Describe any unique attributes of the process by which the HSI Lead elevates HSI risks to project risks.
- Describe any HSI-unique aspects of how human system risk mitigation strategies are deemed effective.
- How experts may be coordinated and used to assess the likelihood and severity of risks to assist project management in making informed decisions.
- How HSI risks to the human will be captured and how these will be elevated through the appropriate channels.
- How defining, characterizing, and tracking HSI risks is integrated with risk tracking for Program and TA's

5.3 HSI Activities and Products

The HSI activities for *<Insert Project Name here>* contribute to mission success, affordability, operational effectiveness, and safety. They enable the accommodation and integration of human performance characteristics into the design of the system with a focus on a cost-effective optimal system. HSI activities consist of systems engineering integration, analyses and evaluation processes throughout the *<Insert Project Name here>* design, development, and deployment phases and through HSI issue identification and mitigation, and periodic assessments performed by domain team representatives.

This section should describe the planned HSI activities for the project that will enable the implementation of the HSI approach and strategy and integrated with other systems identified for the project. HSI activities to be conducted, products of these activities, and the schedule for product submittal and identification of potential problems and risks and how they will be eliminated or mitigated should also be included here. A representative listing of likely HSI-related activities by program phase are included in Table 5.3-1 in the NASA HSI Handbook and specific activities and products should be included below.

In this section, map activities, resources, and products associated with planned HSI technical implementation to each system life-cycle phase of the project. Consideration might be given to mapping the needs and products of each HSI domain by project phase. Examples of HSI activities include analyses, mockup/prototype human-in-the-loop (HITL) evaluations, simulation/modeling, participation in design and design reviews, formative evaluations, technical interchanges, and trade studies. Examples of HSI resources include acquisition of unique/specific HSI skill sets and domain expertise, facilities, equipment, test articles, specific time allocations, etc.

When activities, products, or risks are tied to life-cycle reviews, they should include a description of the HSI success criteria to clearly define the boundaries of each phase, as well as resource limitations that may be associated with each activity or product (time, funding, data availability, etc.).

Table A-3 lists HSI success criteria by life-cycle milestone review.

Table A-3. HSI Success Criteria by Milestone Review

Review	HSI Success Criteria
Mission Concept Review (MCR)	• *HSI Lead identified* • *Elicited stakeholder and user community goals* • *Supported function allocation* • *Developed HSI operational concepts for inclusion in ConOps* • *Documented design constraints* • *Produced high-level HSI requirements* • *Initiated HSI Planning* • *Drafted HSI Plan* • *Supported Feasibility Activities* • *Documented performance metrics and measures*
System Requirements Review (SRR)	• *Established HSI Team including Lead and domain SMEs* • *Baselined HSIP* • *Supported function allocation* • *Generated domain and interface requirements* • *Incorporated HSI inputs into ConOps*
Mission Definition Review (MDR)/System Definition Review (SDR)	• *Documented HSI products and resources in HSI Plan* • *Supported feasibility assessments and modeling including use of mockups, models, and simulations*
Preliminary Design Review (PDR)	• *Refined requirements: formed and validated derived HSI requirements* • *Updated HSI Plan and input into other technical plans, as appropriate* • *Completed technical trade studies* • *Refined interfaces and evaluated design compatibility*
Critical Design Review (CDR)	• *Baselined HSI requirements and verifications* • *Updated HSI Plan and input into other technical plans, as appropriate* • *Documented and incorporated trade study results* • *Incorporated model/prototype results into detailed design* • *Validated components and interfaces against operational concept*
Production Readiness Review (PRR)	• *Updated HSI Plan* • *HSI cost and schedule estimates are within program/project constraints* • *Approved model and prototype results*
System Integration Review (SIR)	• *Documented system integration test results*
Test Readiness Review (TRR)	• *Completed HSI input to system-level test objectives, requirements, plans and procedures*
System Acceptance Review (SAR)	• *Completed HSI requirement verification against end product system* • *Completed end product validation against users' needs* • *Accepted operations support products by end users*

Operational Readiness Review (ORR)/Flight Readiness Review (FRR)	• *Endorsed system certification for operations with humans* • *Endorsed user certification for operations with the system*
Post-Launch Assessment Review (PLAR)/ Critical Event Readiness Review (CERR)/Post-Flight Assessment Review (PFAR)	• *Documented user/maintainer safety, health, and performance* • *Documented lessons learned demonstrating an operational return on HSI investment* • *Documented lessons learned showing implementation of necessary corrections and improvements*
Decommissioning Review (DR)	• *Captured HSI knowledge is placed into program/project documentation system*

A high-level, summary example listing of HSI activities, products and known risk mitigations by life-cycle phase is provided in Table A-4. This table should be tailored for the project for publication within the HSIP.

Key HSI Questions:

- *What is the problem we are trying to solve?*
- *What are the influencing factors?*
- *What are the HSI objectives and issues?*
- *What are the overall project constraints in terms of cost, schedule, and technical performance?*
- *How will we know when we have adequately defined the problem?*
- *Who are the customers?*
- *Who are the users?*
- *What are the customer and user priorities?*
- *What is the relationship of HSI to this project?*

Example typical project HSI activities that may be included in this section:

- *Function Allocation*
- *Task Analyses*
- *Cognitive Task Analyses*
- *HSI Requirements Development and Analyses (See NASA HSI Handbook, Section 5.1.2.6)*
- *HSI Metrics (See NASA HSI Handbook, Section 5.1.2.7)*
- *HSI Requirements Verification and Validation*

This section describes the HSI program tasks by technology development/life-cycle phase in terms of:

- *Task objective*
- *Traceability of the task to requirements*
- *Required resources to complete the task*
- *Estimated time to complete the task*
- *Responsible organization for the task completion and support organizations*
- *Task activities, actions needed to complete the task*
- *Task flow dependencies, on what other tasks does successful performance of this task depend*

Table A-4. HSI Activity, Product, or Risk Mitigation by Program/Project Phase

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
Pre-Phase A	**Concept Studies**	• *HSI Lead selected and assigned during pre-formulation phase* • *HSI effort planned, scaled and tailored* • *Initiate draft HSIP* • *Contribute to ConOps development (include training, maintenance, logistics, etc.)* • *Contribute to early studies/analyses (task analyses, function allocation)* • *Review Supportability Plan* • *Identify domain POCs, develop network to support HSI role in subsequent program activities* • *Support development of AoA Study Plan or similar effort, to include drafting HSI conditions and constraints* • *Decompose applicable standards from NASA-STD-3001 as needed to develop draft Human Systems Requirements* • *Develop HSI inputs to requirements for mission, science, and top-level system, using applicable models* • *Provide HSI inputs to design solutions, technology and maturation strategies* • *Support development of draft Occupational Health Strategy/ Approach, as needed* • *Contribute to initial set of MOEs* • *Support development of Operability Study Report* • *Develop initial concepts for decomposition* • *Support development of products used for human assessments* • *Develop initial definition of human-centered metrics* • *Participate in development of verification and validation reports* • *Support architecture and mission trade-offs and analysis*
Phase A	**Concept & Technology Development**	• *Update HSIP (Baseline)* • *Provide inputs to ConOps (Initial)* • *HSI Team identified before SRR* • *Develop models and mockup(s) for HSI evaluations* • *Human Workload Evaluation Plan* • *Function allocation* • *Validation of ConOps (initial planning)* • *Provide HSI-centric input to document development efforts* • *Evaluate draft Reliability, Maintenance, and Support strategies for appropriate HSI equity, recommend input as appropriate.* • *Participate in test and evaluation (T&E) strategy development (prioritize HSI domain requirements for chosen material solutions, verify process for HSI domain requirements verification)* • *Participate/inform Safety Analysis Process* • *Provide input to RFP: SOW, SRD, SEMP: HSI-related requirements and verification methodology*

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
		• *Support drafting of program documentation insert HSI language as appropriate* • *Participate in Program Risk Assessment activities* • *Baseline Human System Requirements* • *Develop derived requirements to develop lower level design* • *Support development of baseline Occupational Health Strategy/Approach, as needed* • *Support identification of MOEs captured to drive MOPs and TPMs* • *Draft procedures* • *Verify and validate phase product end-items* • *Develop LLC estimates, as needed* • *Track HSI domain risks, as needed* • *Conduct human-centric assessments for established architecture* • *Conduct human error analysis*
Phase B	**Preliminary Design & Technology Completion**	• *Update HSIP to include HSI-related concerns from technical reviews, safety and health risk and strategy* • *Provide inputs to ConOps (Baseline)* • *Develop engineering-level mockup(s) for HSI evaluations* • *Define flight crew environmental and health needs (Aeronautics Research Mission Directorate (ARMD) and Human Exploration and Operations Mission Directorate (HEOMD))* • *Develop HITL usability plan* • *Support development of Human-Rating report for PDR (HEOMD)* • *Provide HSI-centric input to support SRD/Systems Performance Specification development* • *Provide HSI input as required for Acquisition Strategy* • *Developers to verify HSI considerations environmental impact* • *Remain engaged with Risk Assessment activities, update HSI activity as appropriate* • *Provide input for development of Product Support Strategy as required* • *Review System Test Reports, identify HSI concern with M&S outputs, mock-up test, and first article testing* • *Participate in test and evaluation review* • *Support initial development of manufacturing, logistics, training, and testing plans* • *Update HSI inputs to maintenance and logistics planning* • *Review Safety Analysis for accuracy and completeness, identify HSI opportunities* • *Update Human System Requirements* • *Support the update to the Occupational Health Strategy/Approach, as needed* • *Develop refined MOPs* • *Define and track TPMs* • *Develop plans/processes for integration of lower-tier products* • *Use models and prototypes for system design evaluation*

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
		• *Conduct task analyses* • *Update human error analysis* • *Develop project risk management plans* • *Provide HSI project feedback iterations*
Phase C	**Final Design & Fabrication**	• *Update HSIP to include inputs to training and operational phases* • *Conduct First Article HSI Tests* • *Support development of Human-Rating report for CDR (HEOMD)* • *Review Integrated Test results and identify concerns and recommend corrective actions, leverage result for HSI modifications* • *Provide HSI input to Acquisition Program Baseline* • *Update strategy related to incorporating HSI/update HSIP* • *Monitor Test planning, ensure HSI risks are addressed* • *Monitor/track ongoing analysis for HSI opportunities; update input as required.* • *Provide updates based on test results as required* • *Review Maintenance Task Analysis and Procedures* • *Update Human System Requirements* • *Update task and human error analyses* • *Update HITL usability plan* • *Begin developmental HITL Usability Testing* • *Support the update to the Occupational Health Strategy/Approach, as needed* • *Update manufacturing, logistics, training, and testing plans* • *Finalize design updates based on human assessments* • *Integrate HSI inputs evolved from individual component inputs* • *Integrate lower tiered products* • *Provide verification results to show that system models/prototypes satisfy requirements prior to production;* • *Provide validation results to show that system models/prototypes satisfy operational intent* • *Update project risk management plans for production and operational risks* • *Assess detailed design to determine suitability prior to production* • *Provide HSI process feedback iterations*
Phase D	**System Assembly, Integration & Test, Launch, & Checkout**	• *Support Human-Rating report for ORR (HEOMD)* • *Validate human-centered design activities* • *Validate ConOps* • *Verify and Validate Human System Requirements* • *Provide HSI input to system-level test plans/flight test plans* • *Provide requirement verification closure reports and product validation reports from HITL test/demonstration and from HSI inspections and analyses* • *Develop system-level and/or flight test reports that provide validation of analytical models used to predict system performance*

Life-Cycle Phase	Phase Description	Activity, Product, or Risk Mitigation
		• *Provide HSI inputs to operations and maintenance manuals, procedures, and training packages* • *Provide HSI inputs to system design data books and other supporting technical materials for use during Phase E* • *Validate HSI analytical models of the end-product system* • *Provide HSI inputs to the system certification package and to project risk management plans updated with all prelaunch mitigations*
Phase E	**Operations & Sustainment**	• *Monitor of human-centered design performance* • *Review HSI-related incidents and mishap data reports, provide input and constraints for modifications* • *Solicit user feedback, participate in HSIWG to highlight HSI opportunities* • *Review Failure and Discrepancy reports, ensure domain SMEs review relevant reports, provide input for trade-off analysis* • *Update strategy for merging HSI risk management into SE* • *Document achievable HSI requirements for each incremental stage (if evolutionary acquisition)* • *Update HSIP as needed* • *Ensure inclusion of HSI risk and strategy into safety documentation* • *Ensure HSI analyses, impacts and deficiency data is considered as part of modification/upgrade framework* • *Review Maintenance and update maintenance procedures* • *Develop HSI TPM Final Report* • *Provide HSI input to Flight Test Reports* • *Validate HSI models based on flight data* • *Document HSI Lessons Learned* • *Develop technical reports on human system operations*
Phase F	**Closeout**	• *Provide Lessons Learned report* • *Provide HSI input to decommissioning and disposal plan*

6.0 Documentation of Lessons Learned

A key aspect of HSI in both new systems as well as evolutions/iterations of pre-existing systems is the inclusion of lessons learned from past programs or prior iterations of the system. Because of this, the importance of documenting lessons learned as HSI implementation proceeds through time is of critical importance, so that current experiences and development of knowledge and solutions to issues can be learned from and included in future systems. Not only must this documentation occur, it should not be delayed to the end of the program. The end of the program is certainly a time when final lessons and an overall perspective of the successes and failures along the life cycle need to be captured, however the smaller steps along the way should be documented as they occur as well. The transitions from one phase to another within the life cycle (e.g., Phase A->B, and Phase B->C, and so on) are excellent points along the life cycle for documentation of findings and lessons learned. Such lessons can even be included in documentation of exit and entry criteria (KPPs) for each phase transition. In this way the small details are captured and not forgotten by the end of the program, which in some cases (e.g., Orion and CCP) can be several years later, particularly as personnel do tend to transition in and out of programs periodically (taking their experiences with them) and memories for many people growing at least some small degree dimmer over time or possibly lost in the sheer volume of activity in and around such programs.

A lesson learned regarding 'lessons learned' is that they are only helpful when future programs or projects can find them easily and readily should someone go looking. Thus, these lessons learned may be most beneficial not when posted just on an internal website or SharePoint portal, but rather published in a NASA technical note, white paper, or some other such document (even if only available to NASA personnel within the NASA firewall). Similar to a mission report, these end of program publications can serve to document the good, the bad, and the gray that was encountered in the application of HSI within the system design life cycle and ensure that such lessons are found much more readily than by relying on the impermanent nature of program websites or SharePoint portals.

This section of the HSIP should include a description of how lessons learned will be tracked and documented. It may also be updated as part of the HSIP being a living document, to include the lessons learned throughout the engineering life cycle. As this section is created, focus on the need to establish historical context for decisions made, capture new findings, and provide references both for operational phases of the current project and for HSI Leads planning for new projects, it is important to document lessons learned. The HSI Team should establish a system for this documentation approach and implement throughout the life of the project. During design and development this may include capturing design challenges and HSI risks that could be prevented in future projects. During operations phases it is critical to plan for capturing lessons learned from the operators' perspective. Data collected in a manner that is readily available to future HSI Teams will be of value in establishing appropriate requirements and processes for future projects.

Appendix B. HSI in the Project Life Cycle

This Appendix identifies opportunities to recognize and manage HSI during all program/project phases and at major key decision points. The approach that follows incorporates both NASA SE processes and NASA life-cycle phases along with corresponding SMA and Health and Medical activities. For an overview of the HSI emphasis in the NASA life-cycle phases mapped to the SE processes along with the corresponding activities and process from other domains and technical authorities, see Table 5.3-2.

Table B-1 contains the most common products and the expected maturity throughout the life cycle of a program/project. It should be noted that a complete list of products will need to be tailored for the project by the HSI Lead in the HSIP. The HSIP should be updated, as required, when new products are identified. The maturity of these products is based on NPR 7120.5. NPR 8705.2 provides additional insight and detail required from the Safety and Mission Assurance perspective into the types of products required for the health, safety, and performance of humans engaging in operating and living in human-rated space vehicles.

Table B-1. Product Maturity Matrix for Programs and Projects

Phase	**Pre-A**	**A**		**B**	**C**		**D**				**E**	**F**
Milestone Review Product	MCR	SRR	SDR/ MDR	PDR	CDR/ PRR	SIR	TRR	SAR	ORR	FRR	PLAR/ CERR	DR/ DRR
Conceptualization and Architecture												
Concept Documents, ConOps	D	I	U	U								
Function Allocation to Humans (Flight Architecture)	D	I	U	U								
Function Allocation to Humans (Ground Architecture)	D	D	I	U								
HSI Decomposition Models for Requirements Development	D	U	U	U								
HSI Requirements (Project and System)	D	I	U	U								
HSI Requirements (Subsystem)	D	D	D	I								
HSI Inputs to Technology Maturation	I	U	U	U	U							
Human Error Analysis	X	X	D	I	U				U	U		
Human Mockups, Models, Prototypes	X	X	X	X	X	X						
Human Assessments, Human Systems Interactions			X	X	X	X						
Task Analysis	D	I	U	U								
Validate Design to ConOps			X	X	X	X		X		X	X	

Cross-cutting and Management												
HSIP	D	I	U	U	U	U						
HSI-applicable Trade Study Reports	X	X	X	X	X	X						
Measures of Effectiveness (MOEs)	D	D	I	U	U	U						
Measures of Performance (MOPs)	D	D	I	U	U	U						
Technical Performance Measures (TPMs)	D	D	I	U	U	U						
LCC Estimates	D	D	I	U	U	U	U	U	U	U	U	U
HSI Domain Risks	I	U	U	U	U	U	U	U	U	U	U	U
Lessons Learned Reports	X		X	X		X				X	X	X
Production and Operations												
Operations Concept	D	D	D	I	U	U		U	U			
HITL Testing				X	X	X	X	X				
Operate-to Documents			D	D	I	U	U	U	U			
Logistics Documents			D	D	I	U	U	U	U			
Handling and Ops Documents					D	I	U	U	U	U		
Monitoring of Human Performance								X	X	X	X	

Legend: D – Draft, I – Initial baseline, U – Update, X - Applicable

The following sections are subdivided by life-cycle phase supporting the iteration and recursive execution of the SE processes and complementary SMA, Health and Medical processes. The by-phase sections will focus on both the SE processes and HSI goals. As each product or activity is introduced for the first time, regardless of phase, additional detail and reference information will be provided.

B.1 Pre-Phase A: Concept Studies

The key purpose of Pre-Phase A is to "produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected" (NASA SP-2016-6105 Rev2). There are several HSI-related activities that must be initiated or completed during Pre-Phase A. During Pre-Phase A, users and stakeholders for a project or program are identified, high-level requirements are compiled, preliminary design reference mission concepts composed, a preliminary ConOps is developed, and key capabilities of the systems listed. Requests for proposal and contract-related details and deliverables for a future solicitation may be initially considered during Pre-Phase A as well. The mission goals, concepts, high level requirements, capabilities, and constraints must be clearly defined. Early inclusion of HSI Lead and team members ensures that the system concept is optimized for the developers, maintainers, trainers, and other system stakeholders in addition to end users.

Pre-Phase A Purpose

To produce a broad spectrum of ideas and alternatives for missions from which new programs and projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope

Review milestones and Key Decision Points (KDPs) for all phases are defined in NPR 7120.5. The Mission Concept Review (MCR), which supports KDP A for projects, is conducted near the end of Pre-Phase A.

MCR Entrance and success criteria are provided in NPR 7123.1. The MCR is a review of the products of the activities conducted in Pre-Phase A. For smaller projects, there may be a desire to go straight into Phase A and use the System Requirements Review (SRR) as the first KDP and milestone. In this case, it is strongly advised that an informal concept review be held, and that Pre-Phase A activities and products be tailored appropriately.

The relevant goals for the HSI Lead during Pre-Phase A are shown in Table B-2.

Table B-2. Goals and Success Mapping for HSI in Pre-Phase A

Milestone	HSI Goals	HSI Success Criteria
MCR	Elicit Stakeholder Goals	Goals have been captured, quickly matured, and agreed upon by the stakeholder. Any provided requirements, concepts, constraints, budgets, timelines, etc., have been clearly identified and meet stakeholder expectations. For Agency-awarded, industry-led projects, goals have been reviewed by the HSI Lead to ensure alignment with program/project objectives.
	Support Function allocation to Humans	Early identification in the planning of any system; focused on what needs to be done without any “solution bias.”
	Concept of Operations Development Support	HSI input has been provided, evaluated against stakeholder expectations and other project criteria, and successfully integrated within the preliminary ConOps.
	Identify Design Constraints	Preliminary HSI factors, such as the number and skills of users, types of human interfaces, operability, logistics infrastructure, maintainability, and training, have been documented
	Produce HSI Requirements	Draft project/system requirements (based on the ConOps) have been captured at a high level and align with stakeholder expectations. For Agency-awarded, industry-led projects, preliminary HSI requirements supporting the request for proposal have been identified.
	Initiate HSI Planning	Scaling and tailoring of the HSI effort to identify resources and key products needed (HSI team composition, HSIP, analyses, etc.) has been initiated.
	Support Feasibility Activities	HSI feasibility activities have been conducted and findings reviewed. For spaceflight activities, these may include human-centered mockups, models, analysis, and simulations to support consideration of alternative concepts. For aeronautics activities, these may include literature reviews, gap analyses, etc.
	Create Metrics and Measures	HSI data has been captured to provide human effectiveness and performance criteria for the proposed solutions and relationship to the overall mission metrics (matured in the next phase).

The process starts with eliciting stakeholder needs, goals, and objectives for the product and mission. HSI will focus on identifying the touchpoints, interfaces, and systems where humans are involved or allocated to perform functions. The primary product is the preliminary Concept of Operations (ConOps). The ConOps can be in the form of mission scenarios, which include normal operations, as well as scenarios for emergency off nominal and contingency operations. As these scenarios are developed, assumptions, and conceptual decisions are made regarding how the goals and scenarios are accomplished. Functions can be allocated to hardware, software, and humans between flight and ground to create an overall system architecture concept. HSI Leads engage to guide these decisions using best practices, analysis, and assessments for workload, human performance, reliability, impact of these human-centered criteria to the overall mission metrics and other criteria.

The HSI team will also focus on initial requirements development using stakeholder inputs and the initial concept of operations during this phase. See Section 5.1.2.6 for developing HSI-based requirements. For Pre-Phase A, the requirements remain at a high level and the HSI input is focused on function allocation, which will support developing requirements in later phases. See Table 5.1-4, Function Allocation Process, for details on performing function allocation activities with HSI considerations. The HSI team will also produce candidate Measures of Effectiveness (MOEs) that involve human participation. See section 5.1.2.7 for developing and using HSI metrics.

The HSI team should begin drafting the HSI Plan during Pre-Phase A. Capturing the planning materials produced during Pre-Phase A is important to include in the HSIP. See section 5.1.2.5 on writing the HSIP. The HSI team should start to identify which tools, methods, and models will be used to strategically derive and decompose detailed requirements. These methods can include a variety of human assessments, e.g., low-fidelity mockups, task analysis, human constraints and standards, and human-centered design guidance. For a list of these types of resources, refer to Section 5.5 and Appendix G. See Section 3.5.1 on identifying human-centered trade-offs. The HSIP should be in draft form in preparation for MCR. For industry partner-led projects, the HSI team should begin identifying material to be included in the DRD of the RFP. For examples of HSI-related DRDs that can be tailored to meet specific project needs, see Appendix F. It is suggested, at a minimum, that an HSI approach be provided by offerors at proposal submission, followed by their own baselined HSIP for SRR.

B.2 Phase A: Concept & Technology Development

The key purpose of Phase A is to "determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatibility with NASA's strategic plans" (NASA SP-20166105). This is a stage in which the mission concept from Pre-Phase A is refined in a more formal fashion, with increased emphasis towards conceptual development, engineering details, technical risks, and allocation of functions to various systems and sub- systems.

Phase A Purpose

To determine the feasibility and desirability of a suggested new system and establish initial baseline compatibility with NASA's strategic plans. Develop final mission concept, baseline system-level requirements, system technology developments, and program/project technical management plans.

Phase A also begins the development of more formal tasks required to meet the rigor of aeronautics and spaceflight programs/projects. This is still early in the project life cycle, so decisions made here are critical and greatly affect LCC. The architects, designers, and SMEs are still given "room" to assess alternative concepts during the beginning of the phase. By the end of the phase, the concepts, documents, and requirements become firm as system trades and assessments are iterated. Two life-cycle reviews are completed during this phase, the System Requirements Review (SRR) and the System Design

Review (SDR). Goals, top-level system requirements, and the ConOps should be baselined in preparation for these reviews. For SRR and MDR/SDR, HSI practitioners support reviews with HSI-related product submissions, as defined in the HSIP, to communicate HSI details when required, and as evaluators for best practices and standards.

Phase A goals and success criteria for HSI are mapped to relevant milestones in Table B-3.

Table B-3. Goals and Success Mapping for HSI in Phase A

Milestone	HSI Goals	HSI Success Criteria
SRR	Support Function allocation to Humans	HSI support has been completed for all established architecture levels.
	Establish HSI team (required for human-rated programs per NPR 8705.2C and recommended for all projects)	HSI team roster has been developed to include all necessary domain SMEs. Scope of this support may be impacted by program/project funding
	Refine and baseline HSI requirements	Project/system HSI requirements identified at MCR have been baselined and additional requirements have been added to address design constraints, human interfaces, and objectives for all relevant domains.
	Continued ConOps Support	As necessary, additional HSI Inputs are incorporated into the baselined ConOps.
SDR/ MDR	Initiate HSI planning	Key HSI products and HSI resources have been documented in the HSIP, or as input into the SEMP, or other project plan document.
	Support feasibility assessments and modeling	For spaceflight activities, human-centered mockups, models, simulations and analyses have been used to drive lower-level requirements and design trades. For aeronautics activities, findings from literature reviews and other analyses have been used to develop initial mockup, model, simulation, etc. Architecture. Draft training and HITL survey/questionnaire material have been developed.

The activities performed in Phase A build on those performed in Pre-Phase A. The key HSI products started in Pre-Phase A are brought to baseline configuration during Phase A, as shown in Table B-1, Product Maturity Matrix for Programs and Projects. Stakeholder expectations are revisited and used to mature the ConOps document and create MOEs, which must be established for SRR. These stakeholder expectations and other Pre-Phase A products are then used to create top level requirements. The MOEs are used to create MOPs and TPMs as the requirements are matured. Refer to section 5.1.2.7 for additional information on HSI metrics. Most of the requirements work is completed for the top-level architecture by SRR.

The SRR is the first milestone gate for a review of the SEMP, requirements, technical plans, and baseline ConOps document. The HSIP will detail the specific HSI products required for a specific project. The number and types of evaluations, mockups, human interaction assessments, task and user evaluation, HITL tests, etc. will depend entirely upon the nature and scope of the project and the fidelity of the evaluation.

B.3 Phase B: Preliminary Design and Technology Completion

The key purpose of Phase B is for the project team "to complete the technology development, engineering prototyping, heritage hardware and software assessments, and other risk-mitigation activities identified in the project Formulation Agreement (FA) and the preliminary design" (NASA SP-2016-6105).

Processes mature to support the selection of a design solution, leading to plan updates, risk assessments, and the completion of documentation required for the Preliminary Design Review (PDR). Phase A system trades, assessments, technology selection and solutions are iterated, leading to the concepts, documents, requirements, and solutions reaching maturity levels necessary to be reviewed, refined, and baselined by the end of phase B. The conclusion of the phase is a selected preliminary design solution and initial project baseline.

Completion of the PDR precedes the KDP C milestone for projects. For programs, PDR supports KDP I. Entrance and success criteria of the PDR are provided in NPR 7123.1C, Appendix G, Table G-6. HSI practitioners support PDR with HSI-related product submissions, such as updates to the HSIP, and through review of design features from an HSI perspective.

Goals and Success Mapping for HSI in Phase B are provided in Table B-4.

Phase B Purpose

To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling products) requirements and generate a preliminary design for each system structure end product.

Table B-4. Goals and Success Mapping for HSI in Phase B

Milestone	HSI Goal	HSI Success Criteria
PDR	Refine requirements; form and derive Human requirements	System-level requirements have been updated and sub-system requirements baselined. Specific human requirements, TPMS and any sponsor-imposed constraints have been clearly identified, agreed upon with stakeholders, and are consistent with preliminary design metrics.
	Update HSIP and other technical plans	Necessary updates to the HSIP and other pertinent documents (logistics/training plans; HITL surveys and questionnaires) have been made. Definition of technical interfaces (both external entities and between internal elements) is consistent with overall technical maturity and provides acceptable level of risk.
	Conduct trade studies and develop prototypes	Technical trade studies have been completed and prototypes developed to confirm that the operational concept and preliminary design solution are technically sound.
	Refine interfaces and evaluate compatibility	Appropriate modeling and analytical results are available and have been considered in the design.

Since many Phase B activities are continuations or maturations of activities initially begun in Phase A, Phase B shares many of the key items for HSI team members to continue supporting. However, there is often a greater opportunity for engagement in HITL testing using mockups and software simulators, as well as trade studies evaluating various design options. Thus, human factors activities have a key role in Phase B, beyond that of requirements definition, getting into true design evaluation and maturation.

Processes developed in Phase A continue to be refined, allowing system design to be solidified. Product baselines are iterated and updated, human-system interactions evaluated, and trades performed. Decomposition models are selected and used to further derive requirements. Models can be human-centric, such as timing diagrams, crew/operator timelines, behavior diagrams, and operator task analysis. Critical decisions regarding function allocation are made. This may include determinations regarding autonomy and automation as well. The HSI requirements and decomposition models are used to produce initial candidate design solutions and alternatives. HSI Leads should engage to analyze the design solutions for project systems that require extensive human involvement

The key HSI products started in Phase A are updated during Phase B, as shown in Table B-1, Product Maturity Matrix for Programs and Projects. The PDR is the milestone gate for review of the requirements, technical plans, interface control documents, and V&V documents. HSI Lead inputs support meeting PDR Entrance Criteria via the HSIP, Human Rating Certification Package, Verification/Validation Plan, trade-off analyses, and various other products.

Phase B includes selection of a preliminary design using the Pre-Phase A and Phase A products to understand the set of potential solutions, recommended architectures, and inputs to the technology and maturation strategies. The HSI practitioner ensures the preliminary design solution accommodates the human goals and objectives, and concept documents. The HSI Lead assists in the LCC analysis completed during Phase B in order to develop a project baseline by ensuring the analysis includes an evaluation of the cost of operational resources and other HSI activities. See section 3.1 for LCC as it applies to HSI.

B.4 Phase C: Final Design & Fabrication

The key purpose of Phase C is to "complete the detailed design of the system (and its associated integration of subsystems, including the including the operations for the systems), fabricate hardware, and code software" (NASA SP-2016-6105 Rev2). In essence, this phase occurs when all design details are finalized, and the system is prepared for fabrication, integration, testing and verification activities.

In Phase C, the work design solution that was selected in Phase B is prepared for finalization and fabrication. The processes mature similarly, further mitigating risks, developing technological readiness, optimizing design trades, and proceeding through the milestones. The conclusion of the phase is a matured baselined design, achieved by working the processes and proceeding through CDR, Production Readiness Review (PRR), and System Integration Review (SIR). To ensure readiness for production, a PRR and SIR may be held. For many projects, the intent of these reviews will be met during the project's CDR (see NPR 7120.5 for complete details).

Table B-5 provides Goals and Success Mapping for HSI in Phase C.

Phase C Purpose

To complete the detailed system design (and associated subsystems, including operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.

Table B-5. Goals and Success Mapping for HSI in Phase C

Milestone	HSI Goal	HSI Success Criteria
CDR	Ensure detailed design meets system requirements	Detailed human requirements, verification requirements, and integration requirements are developed and baselined. The flow down of verifiable requirements is complete and proper.
	Evaluate interface compatibility	Model/prototype components and interfaces have been modified based on results from HITL Testing conducted prior to PDR. Initial results have been incorporated into detailed design. Validation of components and interfaces against the operational concept has been completed.
	Refine and document technical plans	Technical trade studies have been completed and pertinent information incorporated into detailed design.
	Update SEMP, HSIP, and other technical plans	Necessary updates to the HSIP and other pertinent documents have been made. Definition of the technical interfaces (both external entities and between internal elements) is consistent with the overall technical maturity and provides an acceptable level of risk.

Phase C shares many of the key items for HSI team members to continue supporting. In this phase, the detailed design is matured and baselined based on the results of Phase B. Design evaluation and maturation lead to Phase D assembly, integration, and test activities. The CDR is the major milestone gate for review of the requirements, technical plans, interface control documents, and V&V documents. For HSI practitioners, this milestone represents the conclusion of system design and a shift of focus to further improving system operation through efficiencies in training, operation planning, and maintenance.

In Phase D, the HSI team is focused on the V&V processes that typically begin after CDR, as the end product is assembled and integrated for testing. The HSI team develops the necessary verification closure artifacts for all HSI requirements and further reduces mission risk through validation of the end product for its intended use as described in the ConOps. The HSI team ensures that mission operational products are completed, and operators trained and certified for their work during the operations phase. End product system-level testing and/or flight testing typically occur during Phase D. The HSI team is responsible for implementing the human system aspects of flight test planning, execution, data analysis, and reporting. Phase D HSI goals and success criteria are mapped to relevant milestones in Table B-6.

B.5 Phase D: System Assembly, Integration & Test, Launch

The purpose of Phase D is “to assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations.” (NASA SP-2016-6105 Rev2). For HSI Practitioners, Phase D activities include updating operational procedures, rehearsals and training of operating personnel and crewmembers, and implementation of the logistics and spares planning.

Phase D Purpose

To assemble and integrate the products and create the system (hardware, software, and humans), meanwhile developing confidence that it will be able to meet the system requirements. Launch and prepare for operations. Perform system and production implementation, assembly, integration and test, and transition to use.

Table B-6. Goals and Success Mapping for HSI in Phase D

Milestone	HSI Goals	HSI Success Criteria
TRR	Complete HSI preparation for and endorsement of end product system- level/flight test	Necessary updates to system and sub-system requirements, risk assessments, and other pertinent documents/procedures have been made. HITL testing has provident sufficient data to validate system design, including human interfaces, training documents, risk factors, and other ground/flight test pertinent materials.
SAR	Complete verification of HSI requirements	End product system is shown to conform to HSI requirements.
	Complete end product validation	End product meets the users' needs in the operational mission context.
	Complete development of HSI input to operations support products	End users have accepted operations support products.
ORR/FRR	Certify system for operations with humans	HSI team's endorsement of system certification, leading to operations and sustainment.
	Train and certify users for operations with the system	HSI team's endorsement of user certification, leading to operations and sustainment.

The V&V activities completed in Phase D are particularly relevant to the HSI team. The HSI requirements are verified based upon the verification description and success criteria written and baselined during Phase B. Proper interpretation of these requirements is critical and continuing insight and oversight are needed for the HSI team to ensure success in this phase.

HITL activities conducted in earlier phases that were "pre-declared" for verification credit are now assessed for closing requirements. The HSI team ensures that these HITL activities are consistent with the "test the way we fly" or "test as you fly" or "test like you fly" principle described in NASA/SP-2007-6105, in order to use them for verification closures. The HSI team engages in system-level test/flight test planning, execution, data analysis, and reporting. The team provides HSI input to appropriate system-level test objectives, test requirements, plans and procedures, and test reports. Test data necessary to validate HSI analytical models are collected and used in model correlation.

Validation of the end product system's operational effectiveness is also key in this phase. The HSI team is involved in the execution of validation events and the generation and reporting of results and test reports.

HSI system development products are finalized during Phase D. Test Readiness Reviews (TRR) ensure project readiness for a major test. HSI input to the preparation and planning for tests are part of the TRR package. HSI input to the System Acceptance Review package includes complete V&V reporting on HSI aspects of requirements and operational concepts. It also includes validated analytical models provided by HSI domain experts and HSI input to operational support products such as training documentation, and manuals and procedures for operation and maintenance of the end product system.

B.6 Phase E: Operations and Sustainment

The purpose of Phase E is "to conduct the mission and meet the initially identified need and maintain support for that need". (NASA SP-2016-6105 Rev2). During this phase of the project, the Operations and Sustainment Phase, the mission is executed and the mission objectives that drove the previous project life-cycle phases are achieved. During Phase E, the operations system may continue to evolve in response to experience gained while operating the as-built system. The duration and complexity of Phase E will depend on the characteristics of the mission. In some cases, one system may be operated continuously (e.g., ISS) or repeatedly (e.g., Shuttle) for many years. Such systems and the operations systems that support them may evolve considerably after deployment. In some instances, such as deep space robotic missions (e.g., Cassini, Mars Science Laboratory), there may be no opportunity for flight system evolution, resupply, or repair, while the system that operates the flight system may undergo continued development for multiple years after launch.

Phase E HSI goals and success criteria are mapped to the relevant milestones in B-7. The Post-Launch Assessment Review (PLAR) evaluates the readiness of the spacecraft systems to proceed with full, routine operations after post-launch deployment. The review also evaluates the status of the project plans and the capability to conduct the mission with emphasis on near-term operations and mission-critical events. The HSI team supports the PLAR with an evaluation of human-system aspects of the operational system's readiness to proceed into full operations. The Critical Events Readiness Review (CERR) evaluates the readiness of the project and the flight system to execute a critical event during flight operation. The HSI team provides inputs to CERR, for example, the human-system readiness to perform an extravehicular activity (EVA). The Post-Flight Assessment Review (PFAR) evaluates how well mission objectives were met during a mission, identifies all flight and ground system anomalies that occurred during the flight, and determines the actions necessary to mitigate or resolve the anomalies for future flights of the same spacecraft design. The HSI team describes the success of human-system mission objectives, lessons learned from the flight, and improvements needed for further operations of the system.

Phase E Purpose

To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.

Table B-7. Goals and Success Mapping for HSI in Phase E

Milestone	HSI Goals	HSI Success Criteria
PLAR, CERR, PFAR	Ensure user/maintainer safety, health, and performance	Completion of safe and productive operations of the system to accomplish the defined mission.
PLAR, CERR, PFAR	Identify mission-system anomalies and operational aspects that need improvement in relation to users and maintainers; support implementation of necessary improvements	Documented lessons learned have been provided to the project for future implementation of necessary corrections and improvements.

In Phase E, the HSI team is focused on observing the HSI aspects of the operating system and its users/maintainers to ensure human safety, health, and performance in operations. The team aims to document and communicate aspects of operations that need improvement to achieve project mission success and human safety, health, and performance objectives. A complementary goal is to document those aspects of the mission-system that are fully successful due to HSI effort during development.

Specific HSI team activities in this phase include sustaining engineering of the mission system while it is being operated, operational monitoring, training materials, data collection on the safety, health, and performance of the humans involved with the mission system, and documentation of new HSI knowledge generated during this phase. The HSI team produces technical analyses on potential operational improvements and on successful operational outcomes due to HSI effort performed during system development. For operational flight testing, the HSI team produces reports on flight test objective outcomes that may validate the integrated end product or contribute to the validation of analytical models of the system. As part of HSI sustaining effort, the team evaluates upgraded operational methods and system features as alternative solutions for issues emerging during the mission.

HSI lessons learned are generated from a variety of sources including:

- Inflight testing and demonstration of HSI aspects of the mission/system
- User/crew/operator debriefs and interviews
- Collection of human system data (e.g., faults, losses of efficiency, incidents, accidents)
- Collection of human performance data (e.g., crew time/task time, actions)
- Collection of training efficiency data and decision making data
- Physiologic indicators (e.g., consumables usage, vital signs, illness/injury rates)
- Mission data and reports.

These sources of information should be carefully reviewed and synthesized, lessons learned captured, and HSI findings documented in reports or publications for the ongoing operations and to benefit future programs/projects.

The Phase E milestones ensure user/maintainer safety, health, and performance, and capture HSI knowledge gained over the course of the project.

B.7 Phase F: Closeout

Phase F Objectives

The Closeout Phase, Phase F, is the final phase of the NASA SE process or life cycle. The purpose of Phase F is "to implement the systems decommissioning/ disposal plan developed in Phase E and perform analyses of the returned data and any returned samples." (NASA SP-2016-6105 Rev2).

One role of the HSI team in Phase F is similar to that of Phase E, primarily ensuring that lessons learned are captured, documented, aggregated, and structured so they are easy to find by future teams, and feed forward into future projects. These lessons may impact the revision and development of future requirements or standards. They may suggest new design opportunities or reveal previously unquantified limitations of systems or their operators.

The HSI team will also evaluate the efficacy of mission archive and data products and ensure their readiness for future use. There may be data that has been catalogued throughout a design's operational missions that were to this point unreleased, or accessible via mission personnel and resources that will soon be unavailable, and this phase is a key review opportunity for the HSI team. The interest in the scientific data products produced by the project might also be similarly reviewed for consistency with practices that could have evolved since their original design, as well as software and other tools that emerged to support their consumption and uses as part of a scientific ecosystem.
In Phase F, the HSI team is focused on achieving the safe and successful decommissioning and disposal of

the mission system, while documenting knowledge gained in its development and operations. Successful decommissioning is the end state for the project.

Phase F HSI goals and success criteria are mapped to relevant milestones, shown in Table B-8. The Phase F milestone entrance and criteria are provided in NPR 7123.1C, Tables G-17 and G-18, for the Decommissioning Review (DR) and Disposal Readiness Review (DRR), respectively.

The DR confirms the decision to terminate or decommission the system and assesses the readiness of the system for the safe decommissioning and disposal of system assets. The HSI team may have additional lessons learned from the final stages of the mission, and final values for TPMs evaluated during the operational phase. The Disposal Readiness Review (DRR) confirms the readiness for final disposal of system assets. At this time, the HSI team may provide human-system inputs to decommissioning and disposal planning.

Phase F Purpose

To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.

Table B-8. Goals and Success Mapping for HSI in Phase F

Milestone	HSI Goals	HSI Success Criteria
DR	Capture HSI knowledge gained over the course of the project	HSI knowledge has been placed into the project documentation system.
DRR	Provide HSI support for safe and successful system decommissioning	HSI aspects of system decommissioning and disposal have been incorporated into the project plan.
	Capture final HSI Technical Lessons Learned	Successful capture of lessons learned for program/project archives.
	Archiving HSI data from programs/projects	Successful capture of HSI data needed for program/project archives.

The HSI team supports the system decommissioning and disposal process, where human operations and interactions with hardware/software continue to be essential to the achievement of project goals. The team closes out its work by documenting the value added and lessons learned by HSI to the project and transmitting this information to institutional organizations for archiving and future use.

HSI continues to provide uniquely valuable products during this final phase through retrospective analysis of the project results and input to the human-system aspects of the decommissioning process itself. The HSI team can also lead the generation of lessons learned and final preparation of data for archiving. In each of these cases, HSI methods drive the collection of these data and the generation of products that ensure the data are usable by future information seekers.

The Decommissioning Review (DR) confirms the decision to terminate or decommission the system and assesses the readiness of the system for the safe decommissioning and disposal of system assets. The HSI team may have additional lessons learned from the final stages of the mission, and final values for TPMs evaluated during the operational phase. The Disposal Readiness Review (DRR) confirms the readiness for final disposal of system assets. At this time, the HSI team may provide human-system inputs to decommissioning and disposal planning.

Appendix C. HSI in Safety and Mission Assurance

As stated in Section 5.3.2, the safety and reliability of new and modernized technologies and systems ultimately depend on their interaction with end-users—operators and maintainers. This appendix details the interrelationship between HSI and Safety and Mission Assurance.

C.1 HSI in Applicable SMA-Related Policies, Standards, and Guidelines

For Crewed and Human-Rated missions, NPR 8705.2 (managed by OSMA), requires application of NASA-STD-3001 and FAA's Human Factors Design Standard to human-rated programs/projects. NPR 8705.2 also calls for establishing a formal HSI team for human space flight programs/projects.

For uncrewed/robotic missions, HSI involvement is more flexible in nature as it relates to meeting SMA related programmatic objectives referenced in NPR 8705.4. HSI activities and products can be used to significantly improve effectiveness and efficiencies associated with things like requirements development, requirement flow-down, human-machine interfaces, knowledge transfer, etc., which can be instrumental in improving technical, cost, and schedule performance and reducing overall LCCs.

C.2 Operational Human Reliability Assessment: Qualitative Human Error Analysis (HEA)

Add the following section on HEA as a new section 2 prior to the existing section 2. Operational Human Reliability Assessment:

Qualitative Human Error Analysis (HEA)

Operational personnel make a vital contribution to system safety, especially in situations where human intelligence and adaptability can help manage and mitigate off-nominal circumstances. However, despite positive human contributions to system operations and maintenance, human errors sometimes occur. When they do, they can pose a threat to system safety and performance.

The Human-Rating Requirements for Space Systems (NPR 8705.2C) requires Program Managers to conduct a human error analysis (HEA) for all mission phases, including ground processing, launch preparation, flight operations, and recovery/disposal operations. NPR 8705.2C defines HEA as: "A systematic approach to evaluate human actions, identify potential human error, model human performance, and qualitatively characterize how human error affects a system. HEA provides an evaluation of human actions and error in an effort to generate system improvements that reduce the frequency of error and minimize the negative effects on the system. HEA is the first step in Human Risk Assessment and is often referred to as qualitative Human Risk Assessment." Because HEA is performed as part of the system development process, it is a projective approach requiring the analyst to identify, conceive of, and predict scenarios where human actions could contribute to a catastrophic outcome.

A requirement to consider human error is also included in General Safety Program Requirements (NPR 8715.3D, §1.7.3.1), which state that managers must ensure that designs include considerations for the possibility of human errors. While HEA is a qualitative assessment, the results can also inform probabilistic reliability assessments as required by NPR 8705.5A. Conversely, HEA can draw on data collected to support probabilistic human reliability assessments. Guidance on the conduct of HEA can be found in NESC Position Paper NESC-NPP-18-01368.

C.3 HSI in SMA Activities and Products

Descriptions are provided for how HSI may be integrated into the following SMA activity and product domain areas:

- Activities in the HSI Safety domain (Section C.4)
- Safety activities in the HSI Maintainability and Supportability domain (Section C.5)
- Safety activities in the HSI Operations domain (Section C.5)
- Safety activities in the HSI Human Factors Engineering domain (Section C.6)
- Safety activities in the HSI Habitability and Environment domain (Section C.7)
- Safety activities in the HSI Training domain (Section C.8)

C.4 SMA Activities in the HSI Safety Domain

System Safety involves the application of engineering and management principles, criteria, and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time, and cost throughout all phases of the system life cycle.

Safety factors consist of those system design characteristics that serve to minimize the potential for mishaps causing death or injury to operators, maintainers and supporters or threaten the survival and/or operation of the system or cause cascading failures in other systems.

Prevalent issues include factors that threaten the safe operation and/or survival of the platform; walking and working surfaces including work at heights; pressure extremes; and control of hazardous energy releases such as mechanical, electrical, fluids under pressure, ionizing or non-ionizing radiation (often referred to as "lock-out/tag-out"), fire, and explosions.

Safety analyses and lessons learned are used to aid in development of design features that prevent safety hazards to the greatest extent possible and manage safety hazards that cannot be avoided. For more information on the System Safety domain, consult the System Safety Handbook Vol. 2 (NASA/SP-2014-612).

System safety factors consist of those system design characteristics that serve to minimize the potential for mishaps causing death or injury or threaten the survival and/or operation of the system can be found in NASA-STD-3001 Space Flight Human-System Standard Volumes 1 and 2.

C.5 SMA Activities in the HSI Maintainability and Supportability, and Operations Domains

HSI in the Maintainability and Supportability, and Operations domains can be considered in terms of:

1. Design for Reliability
2. Operational Human Reliability Assessments (HRA)
3. Reliability Centered Maintenance (RCM)
4. Design for Maintainability
5. Design of Maintenance Programs
6. Sustainability/Supportability
7. Identification and Tracking of HSI risks
8. Survivability

1. Design for Reliability

The optimal time to increase the reliability of human systems interactions is during the early concept or design phase, where Human centric operational concepts and/or hardware features can be built into the overall system design and Operations Concept at minimal costs. Reliability engineers can often help in application of the following development guidelines for durable and reliable systems to enhance operational performance, safety, and comfort:

- Designs are capable of withstanding the forces imposed intentionally and unintentionally by crewmembers or operators, and capable of sustaining operations for extended durations with minimal maintenance. Use of proven components of known reliability to the greatest extent feasible under worst case environmental usage.
- Ability to check the condition of critical components. Warning or indication of loss of failure detection for critical components or systems. Where redundant hardware or software is used to satisfy reliability requirements, the

system monitors the health of all redundant elements.

- Systems, components, and elements are isolated from each other such that the failure of one does not cause failure of another.
- Critical systems are designed with redundant or backup systems to enable continued function after any critical failure. Where redundant hardware or software is used to satisfy reliability requirements, the system automatically switches over from a failed element to the redundant element.
- Systems are designed such that they are fail-safe. Design failure paths to control and direct the effects of failure in a way that limits its safety impact. Systems are designed with the ability to sustain damage from their failure effects and limit the safety impact to personnel and crew.
- Critical systems elements are designed such that failure of the primary and redundant systems cannot be caused by a single credible event (e.g., contamination, explosion, temperature, vibration, shock, acceleration, acoustics)
- Contingency planning includes operator procedures after failure detection to enable continued safe flight; evacuating personnel from high-risk areas; and modifying vehicle trajectory to avoid high-risk areas.

Ideally, the design of the system will minimize the need for maintenance thus avoiding the need for human factor elements focused on maintenance activities.

1. Operational Human Reliability Assessment (HRA)

Human operators make an essential positive contribution to system performance and resilience, and systems must be designed and implemented to take full advantage of human capabilities. Nevertheless, from time to time, human error can present a threat to system performance. Human Reliability Assessment (HRA) is a method that involves systematic prediction of potential human errors when interacting with a system. Once they are identified, actions are suggested to try eliminating or reducing their occurrence probabilities, in order to maximize safety and performance of the system or facility. Results of HRA can be entered into risk management actions to reduce the risk to As Low as Reasonably Practicable (ALARP), both by system re-design and implementation of controls and mitigations.

The HRA steps commonly include the identifying of:

- Error types and error producing conditions
- Likelihood of error occurrence
- Opportunities to recover from errors
- Consequence of errors

The HRA should analyze the current design and recommend how to mitigate the errors identified. At the error identification step many reliability and risk analysis tools like Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Hazard and Operability Analysis (HAZOP), can be used. There are also many other HRA specific techniques like SHERPA (Systematic Human Error Reduction and Prediction Approach), HEART (Human Error Assessment and Reduction Technique), THERP (Technique for Human Error Rate Prediction), CREAM (Cognitive Reliability and Error Analysis Method) and ATHEANA (A Technique for Human Event Analysis). The HRA is usually a part of a Probabilistic Risk Analysis (PRA) process. The PRA process also captures the system errors that are mitigated by humans within the system. See the NASA PRA Handbook for information regarding quantitative analysis and probabilistic assessments.

2. Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) is a structured approach to maintenance planning that ensures that scheduled maintenance is tailored to the needs of each component or system, based on the failure patterns of each component, and the consequences should a failure occur.

The RCM process identifies the functions that are most critical and then seeks to optimize their maintenance strategies to minimize systems failures and, ultimately, increase system reliability and availability. By focusing on the most critical functions, the approach also attempts to optimize use of resources to have the greatest impact to the customer.

The RCM approach ensures that systems are maintained at an appropriate level, avoiding over-maintenance and the increased potential for error that this introduces.

3. Design for Maintainability

Early and judicious assessment of supportability and maintainability of system design needs can help ensure system function availability and its contribution to overall mission success.

The design of equipment and systems greatly affects how they are maintained, in terms of complexity, duration, frequency, and safety. R&M engineers can often help in application of the following guidance for designing equipment and systems to facilitate maintenance and ensure proper maintainability:

- Reduce the need for specialized skills, tools, and training.
- Reduce crew time spent on preventive and corrective maintenance.
- Reduce crew cognitive workload.
- Ensure crew safety during maintenance tasks.

Additional maintainability considerations and requirements for designing equipment and systems to facilitate maintenance can be found in in NASA-STD-3001 Space Flight Human-System Standard Volumes 1 and NASA-STD-3001, VOLUME 2, REVISION B.

4. Design of Maintenance Programs

When designing for corrective and preventive maintenance, R&M engineers or other SMA professionals can often help in application of the following guidelines:

- Preventive maintenance should be minimized and require as little crew time as feasible. Preventive maintenance schedules should be sufficiently flexible to accommodate changes in the schedule of other mission activities. If maintenance is necessary and system operations will be interrupted, redundant installations should be considered to permit maintenance without interrupting system operation.
- Maintenance plans for commercial off-the-shelf (COTS) equipment should be appropriate to the space environment, and not simply what is in the recommended ground-based factory standard maintenance plan. Automated fault detection and isolation should be also provided whenever feasible. Calibration, alignment, or adjustment should be easily and accurately accomplished.
- Condition-Based Maintenance (CBM) is the application of technologies, processes, and procedures to determine maintenance requirements based, in large part, on real time assessment of system condition. The necessary information may be obtained by various means, including inspections or the use of embedded sensors. When coupled with reliability centered maintenance, CBM can reduce maintenance requirements and reduce the system down time. The goal is to perform as much maintenance as possible based on tests and measurements or at pre-determined trigger events. A trigger event can be physical evidence of an impending failure provided by diagnostic or prognostics technology or inspection.
    - Key characteristics in implementing the CBM concept include:
        - Hardware - System health monitoring and management using embedded sensors, and integrated data, to the greatest extent feasible.
        - Software - decision support and analysis capabilities both on and off equipment; appropriate use of diagnostics and prognostics; automated maintenance information generation and retrieval
        - Design - open system architecture; integration of maintenance and logistics information systems; interface with operational systems; designing systems that require minimum maintenance; enabling maintenance decisions based on equipment condition
        - Processes - RCM analysis; a balance of corrective, preventive, and predictive maintenance processes; trend-based reliability and process improvements;

integrated information systems providing logistics system response; CPI; Serialized Item Management (SIM)

- Communications - databases; off-board interactive communication links
- Tools - integrated electronic technical manuals (i.e., digitized data) (IETMs); automatic identification technology (AIT); item-unique identification (IUID); portable maintenance aids (PMAs); embedded, data-based, interactive training
- Functionality - low ambiguity fault detection, isolation, and prediction; optimized maintenance requirements and reduced logistics support footprints; configuration management, asset visibility.

5. Sustainability/Supportability

The starting point is to consider the functional and physical architecture of the system. Based on knowledge of similar existing systems, what items are going to most likely fail or require service (inspection, adjustment, cleaning, consumable replacement, etc.). These items should be placed closer to the exterior of the system in the physical architecture of layout to minimize access issues.

Next, from a Sustainability/Supportability perspective, “simplification” and “standardization” should be considered as basic design principles.

Benefits of simplification include:

- Fewer items to fail / wear out
- Fewer items to diagnose
- Less disassembly & reassembly effort
- Lower service parts inventory

Benefits of standardization include:

- Standardized parts and modules can be bought or produced at lower cost
- Parts and modules produced in larger quantities generally have better consistency & quality
- More failure & reliability data for better service planning
- Better accessibility of replacement components; less inventory required to obtain the same spare parts stock-out protection
- Easier for customers and field service personnel to maintain inventory of common standard parts
- Controls, displays, marking, coding, labeling, and arrangement schemes (equipment and panel layout) shall be uniform for common functions of all equipment.

Finally, supportability and sustainability are key elements of overall mission performance:

- Performance-based strategies, including logistics
- Increasing reliability, improving maintainability, and reducing logistics footprint
- Continuing reviews of sustainment strategies.

The following R&M products can be used to support Sustainability/Supportability considerations:

- Failure Modes & Effects Analysis (FMEA)
- Failure Modes Effects & Criticality Analysis (FMECA)
- Level of Repair Analysis (LORA)
- Maintenance Task Analysis (MTA)

6. Identification and Tracking of Safety-related HSI Risk

This activity is performed to evaluate the safety related risks to humans in system operation and maintenance. Human error analysis can be performed for any number of reasons related to the optimization of training, performance, equipment design and safety. Human reliability analysis (HRA) implies a systems model where in conjunction with equipment reliability considerations, the probability of human failure is determined for risk-significant actions and decisions. When performing either human error analysis or human reliability analysis, significant personnel tasks including aspects of human-system interaction described earlier in this chapter will be analyzed in detail such that the circumstances and conditions surrounding them are sufficiently understood to allow for the identification and implementation of error-tolerant design strategies (minimize personnel errors, allow their detection, and provide recovery capability). These insights can be applied to manage the potential for errors through the design of procedures, training, and automation. Significant tasks are those that impact mission success, the safety of system operations, and where personnel safety is an issue. For example, when considering significant tasks for in-flight operations, any errors that have the potential to contribute to loss of mission or loss of crew would be analyzed and the means to make current designs error-tolerant identified. Development teams can develop systems and engineering models, compatible with the risk model developed, to estimate and allocate component, subsystem, and human reliability values throughout the development and operation of the overall system.

7. Survivability

The consideration of survivability should include system requirements to ensure the integrity of the crew compartment and rapid egress when the system is damaged or destroyed. It may be appropriate to require that the system provide for adequate emergency systems for contingency management, escape, survival and rescue.

Survivability includes the elements of susceptibility, vulnerability, and recoverability. As such, survivability is an important contributor to operational effectiveness and suitability.

Incorporating vulnerability reduction features including damage tolerance in system design. These features should balance the use of a robust structural design including hardening and redundancy of critical components, fire prevention/ detection/suppression and software reconfiguration to enable continued use of critical systems under degraded conditions.

Personnel Survivability addresses design features of the total system that reduce susceptibility of operators/users, maintainers and logistics personnel to injury, operational degradation, or failure. Personnel Survivability issues should be considered in the context of the full operational spectrum, including the perspective of personnel who come in contact with the system. Personnel Survivability Analysts determine the range of personnel survivability hazards, and then develop mitigation strategies to address issues identified.

Design and testing ensure that the system and crew can withstand man-made hostile environments without the crew suffering acute chronic illness, disability, or death.

Additional R&M considerations and requirements for designing equipment and systems to facilitate reliability and maintenance can be found in in NASA-STD-3001 Space Flight Human-System Standard Volumes 1 and NASA-STD-3001, Vol. 2, Rev. B.

C.6 SMA Activities in the HSI Human Factors Engineering domain

The consideration of Human Factors Engineering activities needs to include the following:

- Human interface tasks needed to ensure human performance characteristics are addressed as part of the operational, maintainability and supportability design of the system
- Identification of design considerations (such as access, tool design, connector design, size, shape, and mass), that can impact human’s ability to maintain systems.
- Design compatibility requirements.
- Allowing for the positive contribution of human operators.

Safety is concerned with human performance in safety critical environments and human rated systems; therefore, HSI will collaborate with SMA to analyze, design and validate system and human performance requirements. Additionally, Safety may contribute to other Human Factors Engineering activities such as mission and functional analyses, modeling and simulation, system design inputs and evaluations, and design reviews.

C.7 SMA Activities in the HSI Habitability and Environment Domain

All life support considerations, including sustaining requirements and/or protections against space environments, need to be assessed as part of crew survival activities and analysis described in the Safety, Maintainability and Supportability, and Operations domains to ensure that all identified hazards and corresponding risks to safety and mission success are sufficiently addressed and accepted by all relevant customers and stakeholders.

HSI will collaborate with SMA to analyze, design and validate requirements for the physical environment (e.g., adequate personnel space and environment control) and, if appropriate, requirements for personnel services (e.g., medical, and mess) and living conditions (e.g., berthing, education, recreation and personal hygiene) that have an impact on meeting or sustaining system performance or the quality of life. Methods which shall ensure that operator, maintainer and support personnel survivability is analyzed and that results are incorporated into system design to facilitate personnel survivability. Issues to be addressed include protection against fratricide, detection, protection from injury, nuclear, biological, and chemical effects; the integrity of the crew compartment; life support equipment and provisions for rapid egress when the system is severely damaged or destroyed.

C.8 SMA Activities in the HSI Training Domain

Corresponding SMA training requirements and resources need to be identified and implemented in support of the other HSI domain areas to ensure successful execution and assurance of Human related activities over the entire mission development life cycle. Activities include design and validation of operator, maintainer and support personnel training needs based upon human performance requirements developed from system analysis data.

Decision making is a key area within flight operations, both for flight and ground personnel, which becomes even more challenging during real time operations where fast decisions need to be made for crew, vehicle, and mission safety. The key elements of a decision are alternatives, outcomes, and preferences, which may vary just in the transition between design, assembly, and launch operations, to flight operations. This is why human reliability modeling should be combined with knowledge about flight control room operations. This will need a thorough assessment of the factors affecting operator or team decision making. For this reason, decision making deserves a position in human reliability analysis due to conditions and emergency situations they are constantly exposed to. HSI Leads should be involved with training for ground personnel to ensure the models are valid for decision making under multi-criteria situations.

Appendix D. HSI Case Studies

The following case studies provide positive and negative illustrations of key HSI concepts noted in section 2.3 of this document. These case studies comprise examples from NASA and other government and commercial organizations; and describe events from numerous domains that include high-risk missions involving complex sociotechnical systems, including but not limited to crewed and uncrewed aerospace missions. The case studies are intended to provide concrete examples of the value of effective HSI implementation and consequences of ineffective (or absent) HSI. Table D-1 gives a summary of the case studies contained in this Appendix.

Table D-1. Summary of HSI Case Studies

Case Study Title	Human Factors Engineering	Operations	Maintainability & Supportability	Habitability & Environment	Safety	Training
D.1. Inadequate Consideration of Operations During Design: Shuttle Ground Processing		X	X			
D.2. Damage Incurred and Undetected During Repeated Refurbishment and Maintenance Contributed to In-flight Anomaly during STS-93 Launch	X		X		X	
D.3. Expert Knowledge of Human Performance Resulted in Effective Countermeasure for Launch Vehicle Display Vibration	X			X	X	
D.4. Cumulative Effects of Decision-Making, Management Processes and Organizational Culture: The Genesis Probe Mishap	X				X	X
D.5. Training, Simulation, Design and Human Error: The Virgin Galactic Spaceship Two Mishap	X				X	X
D.6. Effective Culture, Requirements and Trade Studies: The Reliable and Maintainable F-119 Engine	X	X	X			
D.7. Inadequate Training, Procedures, Interface Design and Fatigue: The Collision between Navy Destroyer John S. McCain and Tanker Alnic MC	X	X				X
D.8. The Cost of Untested Assumptions About Human Performance: The case of the B737MAX	X	X				X

D.1 Inadequate Consideration of Operations During Design: Shuttle Ground Processing

Abstract

Despite the many successes of the Space Shuttle Program, the shuttle failed to deliver on the proposed rate of flight of 24 flights per year. By 1985, the best the Program had achieved was 8 flights per year, which, in turn, had a significant impact on the LCC of the space transportation system. A study was commissioned to identify Shuttle operations that required "excessive time to complete" and to determine methods and technologies that could reduce LCCs. While some new efficiencies were identified, the evaluation concluded that those efficiencies would have only minimal impact for the in-service vehicle. The evaluation concluded that the consequences of vehicle supportability being de-emphasized early in the design phase could be seen in almost all vehicle sub-systems as well as ground support systems. Drastically reducing the cost of operations could only be met if the designed, fabricated, and delivered hardware had supportability and maintainability designed into it from the beginning of the conceptual study development.

Background

The Space Shuttle was "sold" to the American people and to Congress as a cost-effective way to get to/from low earth orbit. To estimate the cost of operations for the Shuttle, NASA used a projected figure of 24 flights/year and an overall life of 100 flights per vehicle to arrive at an approximate operations cost figure of $100 million per flight. To achieve this launch rate, Program requirements directed that the Shuttle be designed so that it could be launched within 160 working hours after landing of the previous mission, based on a two-shift workday and 5-day work week. Several years into the Shuttle Program, however, it was recognized at all technical and management levels of the program that this turn-around time was unobtainable (by a factor of several times) with the current hardware.

In the mid-1980s, Shuttle ground operations were evaluated to determine methods and technologies that could reduce space transportation system (STS) LCCs. The evaluation included analysis of assembly; test and checkout; logistics; recovery; refurbishment; servicing; payload integration; launch operations; operations management; and ground systems maintenance. One of the objectives of the analysis was to identify Shuttle operations that required "excessive time to complete," as compared against the design goal for the program. While the entire ground operations spectrum was reviewed, Orbiter operations were identified as the area for greatest potential in reduction of turn-around time. Sources of information used for the evaluation included ground operations plans; as-run schedules from prior shuttle turn-arounds; operations and maintenance instructions; and interviews with personnel with personal experience in Shuttle processing. Based on a review of this information, the evaluation identified 40 "issue topics" that impacted operations, with a range of 3-750 individual entries under each topic.

At the time of the evaluation (Fiscal Year 1985), the best flight-rate achieved was 8 flights per year. By this time, the 160-hour turn-around goal had been amended to 680 hours, but the best composite turn-around time that had been observed to date was 1040 hours. The revised cost per flight was estimated at $246 million, with a total estimated LCC per vehicle of $28.6 billion, of which 86% were incurred during operations (as opposed to research and development, design, and manufacture).

Reported Findings

Below are some of the findings identified in the evaluation of shuttle ground operations efficiencies:

- The shuttle was not designed for ease of operations. By limiting front-end design costs, the vehicle turned out to be a proof-of-concept vehicle that was not designed to be operationally efficient.
- Due to limited space in the aft section of the orbiter, the amount of work that could be accomplished at one time was very restricted,

so any work on the engines precluded any other tasks to be worked in parallel. Furthermore, work on the engines required the support of almost all of the Orbiter systems, so work on those systems could not be done at the same time.

- Space Shuttle Main Engines (SSMEs) were designed to be used for 10 flights before they would require any maintenance. At the time of the evaluation no engine had been used for more than one flight without some work being performed.
- The aft section of the Orbiter was described as “a plumber’s nightmare.” So much equipment was installed in a small volume that access was a problem. Damage to electrical connectors occurred as a result of close quarters and people entering and leaving the area.
- While some engine repairs and modifications were accomplished with the engines installed on the Orbiter, engines were removed for major repairs and modifications, which were performed in a separate engine shop. Several problems, however, were identified with the configuration of the engine shop that impeded servicing performance, including:
    - Engine stands not designed for total access to the engine.
    - Shop was not a clean area.
    - Lighting was not adequate.
    - Space was limited.
    - Access to the area was not easily controlled.
- Little thought was given during the design phase to the operation and maintainability of the cabin air recirculation system. To remove the filters, which was performed after every flight, required removal of other equipment to access the filters and shutting off power to the vehicle, which, in turn, prevented simultaneous troubleshooting of many other Orbiter systems.
- Design criteria for the Shuttle called for no special cleanliness requirements. All facilities were to be “good shop practice” only. But over the life of the Shuttle Program, the requirements for contamination control became more demanding. Because the design of the Orbiter Processing Facility did not originally provide for contamination control, additional processes, equipment, and work shifts became necessary to meet the new requirements.
- The efficiency of anomaly resolution was hampered by inadequate numbers of spare or replacement parts and without local maintenance and repair shops. Lack of these led to extensive cannibalization, multiple removal and replacement activities, and the resulting multiple retests required.
- The large amount of time spent during ground processing on troubleshooting anomalies, repairs, cannibalization, and system recertification was based on Program decisions made during the Orbiter design phase, including:
    - Compromises on 160-hour turnaround design criteria because of funding, cost, weight, and schedule.
    - Ignorance of operational requirements.
    - Disregard of the impact of operations workhours and on-line time on LCCs.
- The Shuttle used ordnance devices to perform several different types of operations, including ignition, release, separation, and range safety. Ordnance operations had to be performed slowly and carefully, and due to their hazardous nature, required that all other nearby work be rescheduled or stopped during those operations. These factors were not considered in determining the planned timeline for ordnance operations.
- The documentation system was not optimized for the originator, performer, or verifier; and therefore was an impediment to good work and good records.
- The evaluation estimated a maximum improvement of 10% in STS turnaround time without major modifications to the Orbiter systems, which were not deemed cost effective. It was estimated that all of the proposed efficiency modifications to ground

operations that could be practically implemented could potentially reduce LCCs on Shuttle by up to 5%, but even these modifications would require a significant up-front investment.

- Meeting demands to drastically reduce the cost of operations could only be met if the designed, fabricated, and delivered hardware had supportability and maintainability designed into it from the beginning of the conceptual study development.

Table D-2 provides some specific examples of planned vs. observed timelines for selected ground-servicing activities. It should be noted that some, but not all, of these activities could be performed in parallel with other activities (although, as noted above, opportunities for parallel servicing operations were not always realized).

Table D.-2. Planned vs. Observed Timelines for Selected Ground Servicing Activities

Ground Servicing Activities	Planned Timeline in Hours (based on 160-hr turnaround)	Observed Timeline in Hours
Safing and De-servicing	8	416.5
Mission-Unique Payload Equipment Removal/Installation	24	429.5
Orbiter Scheduled Maintenance	24	1132.5
Propulsion System Scheduled Maintenance	24	893
Unscheduled Maintenance & System Reverification	5	753.5
Hazardous Servicing/Service Disconnects	8	543.5
Contamination Control	0	144
Anomaly Resolution	50	384
Ordnance Operations	8	112
Thermal Protection System Refurbishment	40	2000-3000

Reported Recommendations

Below are some of the recommendations identified in the evaluation of shuttle ground operations efficiencies:

- Future programs must have more consideration of maintainability in early stages of design. Maintainability and accessibility must be “designed in,” not merely “tacked on” at the end of the program.
- Future designs should consider Operational requirements including reliability and maintainability at the same level as performance if our designs are to provide LCCs competitive in the marketplace.
- Design for testability, fault tolerance, transparency to changes, self-improving diagnostics, false alarm discrimination, data compression, and optimum man/machine interfaces must all be firm design requirements.
- Long-term management commitment will be required to effect the necessary changes in design and management methodology.

HSI Takeaways

Good HSI practice includes recognition that there are interdisciplinary, technical challenges that span the program life cycle, for all personnel involved with a given system/mission (e.g., manufacturers, assemblers, operators, maintainers, etc.). HSI challenges exemplified in Shuttle development included:

- Insufficient definition of operational requirements during development phase. The full cost of Operations was not recognized by the NASA Design organizations; particularly the fact that Design typically represents only 3-10% of the LCCs, and that it is in the Design Phase that Operational considerations can provide order-of-magnitude payoffs.

- Concentration on performance requirements but not on operational considerations. The result when supportability takes a back seat to performance is exemplified in the overwhelming LCC and schedule delays evident in the operation of the Shuttle.
- Shuttle design organizations were not responsible for operational cost. If inadequate funds are allocated for the initial design and manufacturing, then proof of concept development for initial flight can take all the allocated funds, leaving none for maintainability and reasonable LCC factors.

In the end, a labor-intensive (high operational cost) vehicle was developed and put into operations. Efforts to find operational efficiencies once the vehicle was in service found that those efficiencies had only minimal impact on overall LCCs. Consideration of the full range of operations, including supportability, during design is critical to a project’s success, by enabling operational efficiencies that provide the greatest opportunity to impact LCCs.

The gap between the concept of operations (ConOps) for ground processing and the actual ground processing of the Orbiter is shown with remarkable clarity in Figure D-1.

Resources

Scholz, A. L., Hart, M. T., & Lowry, D. J. (1987). Shuttle Ground Operations Efficiencies/Technologies Study: Ground Operations Evaluation Final Report, Phase I Vol 2. NAS10-11344.

—Modified from Human Systems Integration Practitioner’s Guide (2015) by Jon Holbrook (LaRC)

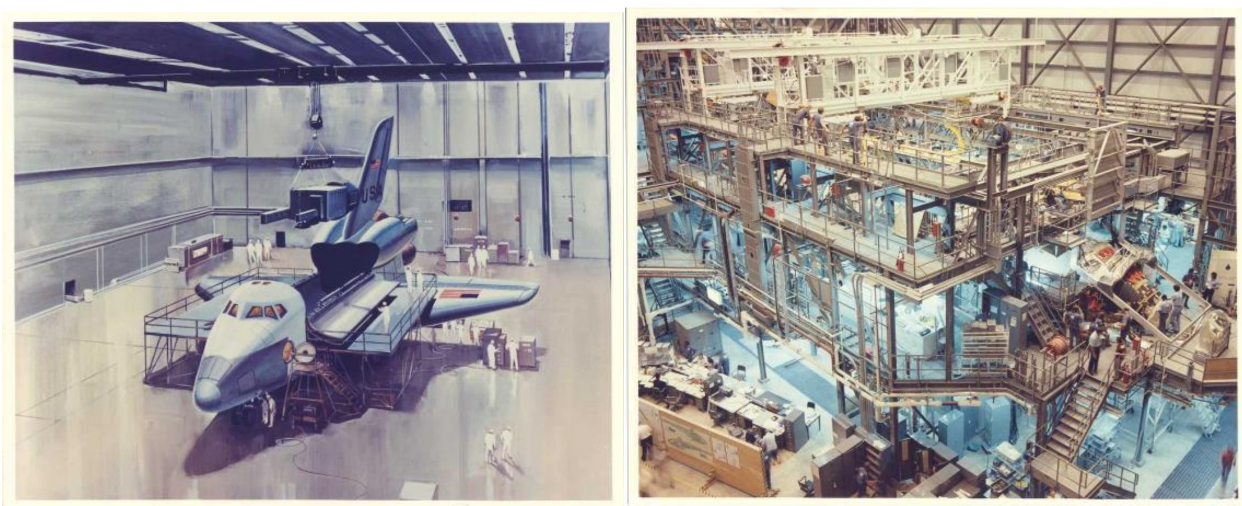

Figure D-1. Shuttle Ground Processing: Conceptual vs. Actual
Source: Bo Bejmuk, Space Shuttle Integration (Lessons Learned Presentation)

D.2 STS-93 Launch: Damage Incurred and Undetected During Repeated Refurbishment and Maintenance Contributed to In-Flight Anomaly

Abstract

During the launch of the Chandra X-Ray Observatory on July 23,1999, an in-flight anomaly occurred a few seconds after liftoff. A power fluctuation caused two Main Engine controllers to drop offline. Fortunately, due to redundancy, the Space Shuttle Columbia was able to successfully reach orbit and avoid an abort. After the successful deployment of Chandra and the safe return of the crew, investigation revealed that the controller failure was due to a wire short in the payload bay. It was suspected that the Kapton insulation on the wire rubbed off against a burred screw head, the result of overtightening of the screw during a maintenance event 4 to 5 years prior to the STS-93 mission. Vibrations led the abraded wire to short during flight. The Space Shuttle Program was grounded for 4 months while a program-wide inspection and wire chafing mitigation effort of all orbiter wiring ensued.

Background

The primary objective of the Space Transportation System mission 93 (STS-93) was to deploy the Chandra X-Ray Observatory. Chandra, the world's most powerful X-Ray telescope, allowed scientists around the world to study some of the most distant and dynamic objects in the universe. Stripped of nearly 7,000 pounds of its own gear to make room for the payload, the orbiter assigned to this mission was Space Shuttle Columbia (OV102), NASA's oldest and heaviest orbiter. Prior to STS-93, Columbia had flown 25 flights.

About five seconds after launch, Mission Control at Johnson Space Center detected a voltage drop on one of Columbia's electrical buses. As a result of this power fluctuation, a primary and back-up Main Engine controller, DCU-A (digital computer unit) and DCU-B (highlighted red in Fig. 1) dropped offline. Given design redundancy, the two remaining controllers, AC-2 and AC-3 (highlighted in yellow and blue, respectively, in Figure D-2), supported all three engines. If there had been any other AC bus issues, one engine of the three on the Orbiter would have shut down. The redundant set of DCUs in each engine controller saved Columbia and her crew from a very risky contingency abort.

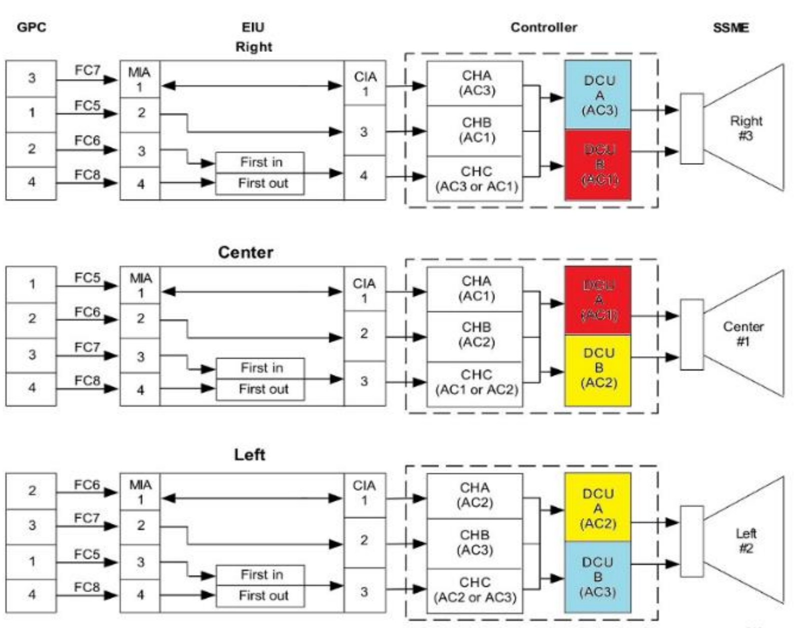

Figure D-2. Main Engine Command Flow [8]

Post-flight inspection revealed soot on a screw head and a hole in an adjacent 22-gauge Kapton insulated wire. The single strand of AC current-carrying 14-gauge polyimide wire was located nearly half-way down the payload bay. The Shuttle Independent Assessment Team (SIAT) reported that the wire had rubbed and chaffed against a burred screw head. The burr was later determined to be the result of overtightening of the screw by a technician during a maintenance refurbishment. Alone, the burr may not have been problematic, but later, during another ground processing event, possibly years after, someone inadvertently stepped on the wiring harness. With the pressure and motion of unintended contact, some of the Kapton insulation rubbed off against the burred screw head. The SIAT suspected the wire damage was pre-existing and was caused 4 or 5 years prior to the flight. See Table D-3 for summary of events leading to the loss of AC buses.

HSI Findings & Recommendations

SIAT Findings:

1. A major difference between Shuttle and aircraft wiring is the high touch labor level and the intensity of maintenance actions on and near Shuttle wiring. While Shuttle wiring was shown to be resistant to damage, extensive damage was present and is attributed to vehicle processing and maintenance. This leads to a concern that adjacent systems may have also experienced damage.
2. The pedigree of the wiring was not well documented. It appeared that a large amount of the wiring damage may have occurred many years earlier. During the life cycle of the Orbiters, there apparently had been variations in repair and inspection processes, changes to quality assurance practices, lack of quality surveillance inspections on wiring and other Shuttle hardware, differences between Palmdale (the location for the Rockwell/Boeing Orbiter Maintenance Down Period (OMDP)) and Kennedy Space Center processes, specification changes, and some degree of wire aging/degradation as a result of environmental exposure and repair actions.
3. The inspection process at the time of the report required inspectors to examine wiring using flashlights, mirrors, and up to 10X magnification. This typically required damage to be visible from the top of the wire bundle or in an area known to be susceptible to damage. There had been at least two instances where wire damage was inside a bundle and not obvious during external inspections.
4. The technicians that worked on the wiring were certified, yet some lacked detailed/specific experience with wiring. Some of these technicians had extensive experience working on many Shuttle operations yet limited time inspecting and repairing wiring. In some cases, the technicians were given training just prior to the start of the wiring inspection and repair effort.
5. The SIAT was concerned that experience and expertise with polyimide insulated wiring within NASA and other agencies was not adequately identified or considered by the NASA and United Space Alliance (USA), the Shuttle ground processing operations contractor, Space Shuttle Program (SSP) wiring team members. The lack of understanding may have influenced the SSP personnel to limit their investigation of the wire incident to only a small subset of potential problems.

Table D-3. Table 1: Series of Events Leading to Wire Short During STS-93

Event	Maintenance Event A – Overtightening	Maintenance Event B – Mechanical manipulation	Launch Day Vibrations	Launch Day Wire Short	Launch Day Voltage Drop
What happened?	Overtightening of screw head by a tech resulting in a burr	Someone stepped on wire harness, causing wire to chafe against burred screw head	Vibrations during launch sequence allowed contact between exposed conductor and exposed metal area on burred screw head	Wire arced to burred screw head and shorted	Voltage drop caused failure of AC 1 in 2 of 3 Space Shuttle Main Engines

SIAT Recommendations:

1. The reliability of the wire visual inspection process should be quantified (success rate in locating wiring defects may be below 70% under ideal conditions).
2. Wire inspection and repair techniques should be evaluated to ensure that wire integrity is maintained over the life of the Shuttle vehicles. Several new inspection techniques had become available that used optical, infrared, or electrical properties to locate insulation and conductor damage, and the SIAT believed these should be explored for use on the Shuttle.
3. The quality assurance program should be augmented with additional experienced NASA personnel.
4. Technician/inspector certification should be conducted by specially trained instructors, with the appropriate domain expertise.
5. NASA and USA quality inspection and NASA engineers should review all criticality-1 (CRIT 1), which is a single failure that could result in loss of life or vehicle, system repairs.
6. A standing wiring team to monitor wire integrity and take program wide corrective actions was needed. It should include technicians, inspectors, and engineering with both contractor and government members. The chair of the team should have direct accountability for the integrity of wiring. The techniques that can detect an exposed conductor that has not yet developed into an electrical short should be evaluated.

HSI Takeaways

- Failure to incorporate thorough and early inclusion of HSI and Human Factors as part of the decision process and development of complex systems increases the potential for failures. These principles should be applied to ground operations for all launch systems.
- As the SIAT recommends, human error management and development of safety metrics should be supported aggressively and implemented program wide.
- The vibrations during launch cannot be replicated during ground testing.
- Due to the quick turnaround times of the orbiters, wiring issues caused from multiple maintenance events can often be overlooked.
- Refining and standardizing wire inspection criteria to allow for minimal damage, quantifying and evaluating current wire visual inspection processes, and certifying technician/inspector by specially trained instructors, can help reduce human error associated with maintenance tasks.
- The SIAT findings highlight several missed opportunities for HSI applications. These include:
    - Wiring processes
    - Evaluation of the integrated manufacturing, maintenance, refurbishment, and flight preparation of Space Shuttle Orbiters
    - Specification of correct scaffolding and process tooling to avoid damaging elements of the vehicle such as wiring
    - Evaluation of the inspection process and the design of the systems that should be amenable to inspection

Resources

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—Contributed by Kristy Yun (LaRC)

D.3 Expert Knowledge of Human Performance: Effective Countermeasure for Launch Vehicle Display Vibration

Abstract

Astronaut crews experience significant whole-body (including head and eye) vibration during space launch that is caused by interactions of the vehicle structure with its propulsion systems and the surrounding atmosphere. The resulting visual blur can be severe enough to hamper the ability to read information displays. A Human Factors study, conducted in the laboratory, demonstrated the effectiveness of a strobe countermeasure to improve the readability of a stationary panel display viewed by observers undergoing whole-body vibration, restoring reading performance to levels similar to those achieved under non-vibrating baseline conditions.

Background

Initial analyses in 2007-2008 indicated that the Constellation Program's Ares-I launch system's solid rocket motor would generate narrowly-tuned vibration that could compromise the ability of astronauts in the Orion crew vehicle to read and process visual information presented via electronic displays or printed placards. NASA engineers sought input from Human Factors experts to empirically investigate the impact of these vibration episodes on flight crews' ability to perform necessary operational tasks such as the monitoring of flight displays. Afterward, armed with understanding of the Ares-I/Orion vibration environment and knowledge of the effects of stroboscopic illumination on human visual perception , the Human Factors experts developed a countermeasure, akin to techniques employed in industry for visual inspection of rapidly moving machinery, for eliminating the apparent visual blur of a stationary object viewed by a vibrating observer. The countermeasure demonstration was implemented by modifying a conventional video display panel's controller so that its backlight could be strobed on-and-off in synchrony with the dominant frequency of vibration measured at the crew member's seat.

Results

The strobe countermeasure improved task accuracy in reading performance to levels that were statistically indistinguishable from the equivalent non-vibrating, constant-illumination baseline. Moreover, the strobed countermeasure significantly improved response times during vibration relative to the non-strobe baseline.

HSI Takeaways

Interactions among system components and resulting effects on crew performance should always be considered during design. In this case, the launch vehicle vibration is transmitted to the crew vehicle, including the crew seats, the display screens, and the crewmembers themselves.

HSI has its own body of knowledge, methods, tools, and products. This solution, derived from a human factors lessons learned for rapidly moving machinery, leveraged knowledge of the human visual system to develop an inexpensive yet effective countermeasure.

Resources

https://www.sciencedirect.com/science/article/pii/S0094576512002664

U.S. patent in the public domain on the technology: M.K. Kaiser, B.D. Adelstein, M.R. Anderson, B.R. Beutter, A.J. Ahumada, & R.S. McCann: "Stroboscopic Image Modulation to Reduce the Visual Blur of an Object Being Viewed by an Observer Experiencing Vibration," US Patent 8,711,462, April 29, 2014.

—Contributed by Damon Stambolian (KSC)

D.4 Cumulative Effects of Decision Making, Management Processes and Organizational Culture: Genesis Probe Mishap

Abstract

The Genesis Probe mishap is a quintessential example of James Reason's Swiss Cheese model of accident causation (Reason, 1990). This model states that although many layers of defense lie between hazards and accidents, there are flaws in each layer that, if aligned, can allow an accident to occur. For the Genesis Probe, these flaws were evidenced in mechanical design, training, role and responsibility definitions, staffing, coordination, project management, systems engineering, and NASA culture. The purpose of the Genesis Probe was to collect samples of solar wind particles and return them to Earth. On September 8, 2004, the Genesis sample return capsule drogue parachute did not deploy during entry, descent, and landing operations, and the Sample Return Capsule struck the desert floor at 193 mph. A Type A Mishap Investigation Board (MIB) was established on September 10. The MIB identified the proximate, or direct, cause to be erroneous design: The G-switch sensors were in an inverted orientation and were unable to sense capsule decelerations to initiate parachute deployment. The six root causes (events, conditions or organizational factors) that contributed to this mishap and MIB recommendations are discussed.

Background

Due to spiraling costs and schedule, in 1992, Daniel Goldin was appointed NASA Administrator by George H.W. Bush with the directive to cut costs without sacrificing performance. The principles of what came to be known as Faster, Better, Cheaper (FBC) were rooted in the Air Force "Skunk Works" group started in the 1940s. Early FBC mission successes led to overconfidence, and NASA missions became too aggressive for their constraints (Launius and McCurdy, 2015). The FBC approach broke when proposed missions began getting more ambitious without a change in schedule and cost cap. The Genesis Probe mission had the typical characteristics of an FBC mission: a lower budget, small budget reserves, government-industry partnering rather than the traditional government oversight, and use of heritage systems.

The Genesis Probe was based on the earlier Stardust Probe designed by Lockheed Martin Space Systems (LMSS) under contract with the Jet Propulsion Laboratory (JPL). Both Sample Return Capsules (SRC) were approximately 5 ft in diameter and weighed about 500 lbs. Stardust, the heritage design, was launched in February 1999 to collect comet and interstellar particles and had a mission duration of almost 7 years. Genesis was launched 2.5 years later in August of 2001 to collect solar particles with a mission duration of just over 3 years. Therefore, Genesis was scheduled to return to Earth before the heritage Stardust Probe.

NASA selected this mission with only 11-percent budget reserve at confirmation. All involved (NASA, JPL, and LMSS) were convinced that, because of the assumed heritage design, this was an acceptable position. However, once heritage was broken and design issues arose, and with limited reserves expended, there was only one place for funds to be found -- the contractor's profits. Eventually, JPL Project Management asked LMSS to give up fee to cover other non-LMSS risk issues and avoid a project overrun of the cost cap. Later, due to a launch slip and NASA-mandated changes, the project obtained more money for the JPL Project Team; and was able to re-establish fee for LMSS through incentives to be efficient during flight operations.

Around the time of the PDR and the Confirmation Review, the Genesis project recognized that the SRC avionics units (AU) required more functionality than was available from the Stardust design, including additional relays and a new motor control board. As a result, the SRC-AU design was upgraded to six cards, which was well beyond the volume of the original box. The six boards were installed on edge into two separate boxes. At this time, some engineers believed that Stardust heritage had been violated, others felt that the pyro initiation aspects of the design maintained Stardust heritage. A group at LMSS handled the SRC-AU changes based on a Stardust heritage schematic that contained no indication of any sensitivity of the mechanical G-switch sensors to orientation. In addition, the G-switch sensor part-level drawing was not understood by the layout engineer, because the mechanical G-switch sensor mechanism was outside of his training and experience as an electrical engineer. As a result, the relay card drawing was laid out with the G-switch sensor in an inverted orientation from that necessary for it to function during entry. Furthermore, the SRC-AU designers had insufficient mechanical systems or guidance, navigation, and control systems experience to recognize the orientation issue with their design. Concurrent with this, a new LMSS Product Integrity Engineer (PIE) was assigned to the project. With the typical list of problems that go with a project, the novice PIE was most concerned with a problem that was threatening the project schedule and therefore the cost-cap established by the FBC philosophy.

Prior to the FBC culture, requirement testing, systems engineering, and project technical reviews would have caught the G-switch sensor inversion mistake. However a centrifuge test to verify the directionality of the G-switch sensors was replaced with a drawing inspection. A record of this change is only evident in a single bullet point on a slide set, and no one on the team remembers a discussion about that significant change. Other FBC-linked consequences contributed to the design flaw not being caught: Systems Engineering at LMSS was understaffed; they had not assigned end-to-end entry, descent, and landing responsibility to anyone; NASA did not use oversight over the LMSS design; and critical NASA technical reviews were not attended by key individuals necessary for an adequate peer review.

Genesis had successfully gathered solar particles and was on its return trajectory to the Utah Test and Training Range. A drogue parachute was intended to slow the capsule and provide stability during transonic flight. The plan was to capture the SRC during its descent on a parafoil by a waiting helicopter. Operation of the spacecraft appeared nominal until the expected deployment of the drogue parachute at approximately 108,000 ft (33 km) altitude. No drogue or parachute was observed, and the SRC impacted the desert floor at 193 mph. The inverted orientation of the G-switch sensor had not triggered the drogue parachute deployment.

Official Findings, Recommendations, and Conclusions Related to HSI

The MIB identified six root causes of the mishap:

- Inadequate Management by the Project and Systems Engineering, including insufficient critical oversight that might have identified the key process errors that occurred at LMSS during the design, review, and test of the spacecraft. This process was consistent with the FBC culture of the time.
- Inadequate Systems Engineering Processes, including poorly written requirements, verification processes, and non-existent reviews of SE progress.
- Inadequate Review Process at all levels of review, including a special Red Team review. Reviews were superficial and perfunctory.
- Unfounded confidence in a heritage design. This refers to people on the team inappropriately thinking that heritage designs require less scrutiny and are inherently more reliable than new designs.
- Failure to "Test as You Fly". This refers to the failure to treat the G-switches as sensors that need to be tested in a centrifuge.
- FBC philosophy encouraged increased risk-taking by projects to reduce costs. In addition, JPL chose to reduce their oversight of the technical progress of the project.

MIB Recommendations centered on improving the rigor of the technical review process of new designs, heritage designs and Systems Engineering. In addition, it was identified that effective reviews should identify requirements, design, verification, and process issues early to avoid costly overruns or tragic failures.

The HSI representative on the MIB analyzed interview and survey data collected from the 23 key players on the Genesis team. Four layers of contributions were identified and summarized as follows:

1. **Individual human error in engineering and design.**

"Designer error" included both the ambiguity about the G-switch drawings and proper methods for verification of the G-switch function.

2. **Preconditions relating to team coordination and individual readiness.**

Preconditions related somewhat to team coordination issues (as evidenced by some role confusion and some rigidity in the systems engineering and project management processes seen in the interviews), although the organizational communication survey generally showed a strong social network among all the major parties. Another precondition discussed in main MIB report was the issue of personal readiness, particularly that an electrical engineer alone was ill-equipped to cope with some of the mechanical issues that arose with the G-switch implementation.

3. **Flaws in project management and systems engineering practices.**

The formal requirements and verification processes tended to prevent appropriate 'drill-down' into issues that should have been examined in detail. In other words, the formal and hierarchical processes acted as a barrier to some extent, perhaps leading to a false sense of security that issues had been properly raised and resolved at some other level. This is not to say that formal hierarchical processes are bad, but that it still takes appropriate judgment and action to wield them effectively. The ambiguity about the notion of 'test' itself leads systematically to assumptions that can often go unexamined.

4. **Organizational factors related to the pervasive influence of the Faster-Better-Cheaper corporate culture at the time of the Genesis design.**

The organizational climate of reliance on heritage and the values of "Faster" and "Cheaper" tending to trump "Better" were another set of latent factors.

HSI Takeaways

There are interdisciplinary, technical challenges that span the program life cycle. These challenges are present not only in the mission itself, but in organizational policies, procedures, processes, reviews, and oversight.

In a large organization such as NASA, upper management needs a keen awareness of the cascading effects of cultural directives. In this case, the FBC culture drove coping strategies that were harmful to the mission. Cost-caps meant that each person became responsible for multiple jobs, stretching their ability to see process weaknesses, resulting in assignments given to individuals lacking the required proficiency and driving the reduction in contractor oversight by NASA.

Resources

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—Contributed by Bettina L. Beard (ARC)

D.5 Training, Simulation, Design and Human Error: Virgin Galactic Spaceship Two Mishap

Abstract

On October 31, 2014, the SpaceShipTwo (SS2) reusable suborbital rocket, operated by Scaled Composites LLC (Scaled), broke up into multiple pieces during a rocket-powered test flight and impacted terrain over a 5-mile area near Koehn Dry Lake, California. The pilot received serious injuries, and the copilot received fatal injuries. SS2 was destroyed, and no one on the ground was injured as a result of the falling debris. SS2 had been released from its launch vehicle, White Knight Two (WK2), about 13 seconds before the structural breakup. SS2 was equipped with a feather system that rotated a feather flap assembly with twin tailbooms upward from the vehicle's normal configuration (0º) to 60º to stabilize SS2's attitude and increase drag during reentry into the earth's atmosphere. A forward-facing cockpit camera and flight data showed that the copilot unlocked the feather just after SS2 passed through a speed of 0.8 Mach. One of the pertinent regulations relating to the issuance of an experimental permit is 14 CFR 437.55, "Hazard Analysis," which, among other things, requires the applicant to identify and describe those hazards that could result from human errors. In its SS2 hazard analysis, Scaled did not account for the possibility that a pilot might prematurely unlock the feather system, allowing the feather to extend under conditions that would cause a catastrophic failure of the vehicle structure. This accident demonstrated that mistakes could occur even with a flight crewmember who had extensive flight test experience and had performed numerous preflight simulations.

Background

Scaled was responsible for developing a "reliable, reusable, and affordable suborbital commercial space tourism system for Virgin Galactic." Accordingly, Scaled developed and built WK2 as the high-altitude launch platform and SS2 as the reusable suborbital rocket. The design mission for SS2 consisted of the following phases:

- Air launch from WK2, which occurs at an altitude of about 50,000 ft;
- Boost, during which SS2's rocket motor propels the vehicle from a gliding flight attitude to an almost-vertical attitude—the maneuver during which SS2 pitches up from horizontal to vertical flight is referred to as the "gamma turn," which occurs after SS2 accelerates from subsonic speeds, through the transonic region, to supersonic speeds;
- Apogee (maximum altitude), which occurs at an altitude of about 360,000 ft or above—the rocket motor is cut off at an altitude of about 150,000 ft, after which SS2 coasts to apogee;
- Reentry, which occurs with SS2 in a "feathered" configuration, allowing the wings to rotate upward to stabilize SS2's attitude and increase drag;

- Glide, which follows SS2's transition from a feathered to an unfeathered configuration; and
- Landing (unpowered).

During the accident flight, SS2 was flown by two Scaled test pilots. The pilot (in the left seat) was the pilot flying and the pilot-in-command, and the copilot (in the right seat) was the pilot monitoring. The accident flight occurred during SS2's fourth powered flight test (referred to as PF04). The objectives of PF04 included conducting a 38-second burn of a new rocket motor and a feathered reentry at a speed that exceeded 1.0 Mach (1.2 Mach was planned).

After release from WK2 at an altitude of about 46,400 ft, SS2 entered the boost phase of flight, during which the vehicle was to transition from a gliding flight attitude to an almost vertical attitude and accelerate from subsonic to supersonic speeds. The flight test data card used during the accident flight indicated that the copilot was to unlock the feather during the boost phase when SS2 reached a speed of 1.4 Mach. However, a forward-facing cockpit camera and flight data showed that the copilot unlocked the feather just after SS2 passed through a speed of 0.8 Mach. The feather actuators were not designed to hold the feather in the retracted position during the transonic region, and, as a result, the feather extended uncommanded, causing a catastrophic structural failure.

Official HSI Findings & Recommendations

In its investigation of this mishap, the National Transportation Safety Board (NTSB) found that:

- Although the copilot made the required 0.8 Mach callout at the correct point in the flight, he incorrectly unlocked the feather immediately afterward instead of waiting until SpaceShipTwo reached the required speed of 1.4 Mach.
- The copilot's action of unlocking the feather after the 0.8 Mach callout occurred during a particularly dynamic and high workload phase of flight, in which a sequence of multiple flight-critical tasks needed to be accomplished in a limited time frame.
- The flight crew were experiencing vibrations and loads immediately after the rocket motor ignited that were not replicated in their simulator training. Cockpit image recording after rocket ignition showed that the pilots' voices were strained and that the copilot did not initially place his hand on the feather lock handle in the correct place.
- The NTSB concluded that the copilot was performing under time pressure and with vibration and loads that he had not recently experienced, which increased the opportunity for errors.
- Although some SS2 program test pilots, engineers, and managers were aware that unlocking the feather during transonic flight could be catastrophic, no warning, caution, or limitation in the SS2 Pilot Operating Handbook specified the risk of unlocking the feather before 1.4 Mach. Furthermore, the hazard analysis performed by Scaled failed to account for the possibility that a pilot might prematurely unlock the feather system.
- Scaled assumed that pilots would correctly operate the feather system every time and follow normal and emergency procedures for a given situation, because of the training they received . However, Scale did not determine a specific training protocol that would measurably and reliably reduce the possibility that the feathering task would be performed incorrectly.
- The NTSB determined that the probable cause of this accident was Scaled Composites' failure to consider and protect against the possibility that a single human error could result in a catastrophic hazard to the SS2 vehicle. This failure set the stage for the copilot's early unlocking of the feather system, which led to the subsequent aerodynamic overload and in-flight breakup of the vehicle.

The NTSB Recommendations included:

- Develop and issue human factors guidance for operators to use throughout the design and operation of a crewed vehicle.
- Implement steps in the evaluation of experimental permit applications to ensure that applicants have (1) identified single flight crew tasks that, if

performed incorrectly or at the wrong time, could result in a catastrophic hazard, (2) assessed the reasonableness, including human factor considerations, of the proposed mitigations to prevent errors that could result from performing those tasks, and (3) fully documented the rationale used to justify related assumptions in the hazard analysis.

HSI Takeaways

By not adequately considering, documenting, or preparing for potential causes of uncommanded feather extension on the SpaceShipTwo vehicle, Scaled Composites missed opportunities to identify the design and/or operational requirements that could have mitigated the consequences of human error during a high workload phase of flight.

Human factors should be emphasized in the design, operational procedures, hazard analysis, and flight crew simulator training to reduce the possibility that human error during operations could lead to a catastrophic event.

Human error associated with tasks that can significantly impact safety is most reliably addressed using task-specific procedural and/or design mitigations that use redundancy or error checking to reduce the severity of an outcome, because the possibility of a single human error cannot be reliably predicted or eliminated.

Even the best simulations and training experiences cannot be certain to prepare operators for all of the conditions and situations they may encounter in actual operations. Design mitigations can help further mitigate the likelihood and consequences of human errors and performance limitations.

Resources

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—Contributed by Michael Bell (KSC)

D.6 Effective Culture, Requirements and Trade Studies: The Reliable and Maintainable F-119 Engine

Abstract

The Advanced Tactical Fighter (ATF) program was started in 1981 to create a military jet that would guarantee air superiority. Two contractor teams competed for the fighter contract. In 1991, the ATF contract was awarded to the Lockheed team's F-22, powered by Pratt & Whitney's F-119 engine. This award was based in part on the fact that the F-22's engines offered superior reliability and maintainability (Cost Estimation of HSI, Kevin Liu, 2010). This came about because the USAF placed an emphasis on reliability and maintainability from the beginning of the ATF program, considering that over 50 percent of the USAF budget was devoted to logistics and predicted to worsen. Pratt & Whitney chose to emphasize designing for the maintainer throughout all aspects of the program and conducted ~200 trade studies as contracted deliverables. They also conducted thousands of information trades for internal use. As a result, the F-119 engine could be maintained with only 5 hand tools and all line replaceable units (LRUs) were "one-deep," i.e., replaceable without removal of any other component. Furthermore, the LRUs could be removed with a single tool within a 20-minute window, even while wearing hazardous environment protective clothing.

Background

In November 1981, the ATF program was created to design a military jet able to guarantee air superiority against the Soviet Union. In 1983, a Lockheed/Boeing/General Dynamics team contracted into competition with Northrop Grumman. In 1991, the ATF contract was awarded to the Lockheed team's F-22, powered by Pratt & Whitney's F-119 engine (see Figure D-3). An important consideration in the contract's award was that the F-119/F-22 demonstrated superior supportability and maintainability.

Figure D-3. F-119 Engine Cutaway (Pratt and Whitney, 2002)

Context

When the F-22 program was approved in 1981, the Air Force placed an early emphasis on supportability and maintainability and maintained this emphasis throughout the program's life cycle. In June 1983, the Army, Navy, and Air Force signed a joint agreement to emphasize to the defense contractor communities the critical importance of improving operational readiness and supportability. At that time, system logistics costs were over 50% of the total Air Force budget and rising. The two prime competitors for the F-22 contract—Lockheed with Pratt & Whitney as their engine developer, and Northrop Grumman with General Electric as their engine developer—were first notified of the DoD's sustainability concerns.

The customer identified a priority on HSI in their requirements

In 1984, to address the growing escalation of systems logistics expenditures, the Air Force created a Reliability, Maintainability & Sustainability (RM&S) program. In addition to reducing LCC, the RM&S program sought to address reliability and durability problems that had plagued engines powering the existing Air Force's F-15 Eagle. Developed in the 1970s, the F-15 was specifically designed to counter the Russian MiG-25, with requirements emphasis placed on performance not RM&S.

Unfortunately, the high performance of the F-15 engine meant that it was more prone to failure and downtime. By the 1980s, the Russian air superiority threat was no longer as pressing, the growth in logistics costs was deemed unsustainable, and supportability began to be emphasized over performance. As a result, the Air Force wanted improved RM&S not only on the engine for the F-22, but on the system as a whole. Specific supportability goals for the F-22 were defined by the RM&S program and announced to the prime contractors. These included reducing the parts count, eliminating maintenance nuisances such as safety wire, reducing special-use tools, using common fasteners, improving durability, improving diagnostics, etc.

Understanding customer needs

Pratt & Whitney decided to center its competitive strategy on RM&S superiority, understanding the customer had made RM&S critical to the competition. For the F-119 engine, Pratt & Whitney decided not only to meet the Air Force's RM&S requirements, but to emphasize designing for the maintainer throughout all aspects of the program.

Pratt & Whitney conducted approximately 200 trade studies using evaluation criteria such as user safety; supportability; reliability; maintainability; operability; stability; and manpower, personnel, and training. Figures of merit were developed for the trades to determine which human-centered disciplines should participate in each trade study. Pratt & Whitney also brought their engineers to Air Force maintenance facilities so that the engine designers could experience first-hand the challenges created for maintainers by past designs. Maintainers showed how tools were poorly designed, manuals had unclear instructions, and jobs supposedly meant for one person took two or more to complete safely. Lessons learned were passed on to every engineer on the F-119 engine design team and ground rules for maintenance design were established.

Integrated Product Development teams were established so that multiple, diverse discipline experts worked side-by-side on the design. Design changes were approved by a Configuration Control Board of senior engineers from multiple technical disciplines. Design review processes ensured the work of one group did not create unforeseen problems for another. Proactive leadership made certain that HSI principles were followed.

One of the most important requirements for the F-119 was that only five hand tools be needed to service the entire engine. (In the end, the F-119 engine required five two-sided hand tools and one other, for 11 tools total.) Other requirements included: all LRUs were to be serviceable without removal of any other LRU, and each LRU was removable within 20 minutes.

Subassembly drawings required annotation with the tools needed for service. Maintenance must be possible while wearing hazardous environment clothing. Maintenance tasks must accommodate maintainers in the 5th percentile female to the 95th percentile male range. Built-in test diagnostics were to eliminate the need for special engine diagnostic equipment. Training was computer-based.

To verify the maintainability of their design, Pratt & Whitney developed several full-scale mock- ups of the F-119. Though requiring a significant investment this ability to intimately evaluate the human/system interaction with maintainers allowed engineers to confirm their designs achieved maintainability goals.

HSI Findings & Recommendations:

HSI efforts contribute to competition success

In 1991, both Pratt & Whitney and GE were awarded contracts worth $290 million to build prototype engines for flight evaluation. GE chose to emphasize the flight performance of its F-120 engine over RM&S, though the F-120 did meet the Air Force’s RM&S requirements. Despite the F-120's superior performance in the air and higher thrust-to-weight ratio, on April 23, 1991, the Air Force chose the combination of Pratt & Whitney’s F-119 and Lockheed’s YF-22 to be developed into the F-22. Pratt & Whitney had demonstrated a better understanding of the Air Force’s RM&S needs, having invested more time and money into HSI demonstration than had GE. Pratt & Whitney had presented a management plan and development schedule that the Air Force considered sensitive to their needs. On August 2, 1991, contracts worth $11 billion were awarded to Lockheed and Pratt & Whitney demonstrating the Air Force’s strategic investment in and commitment to HSI.

HSI Takeaways

Key HSI success factors

The actions of both the Air Force and Pratt & Whitney were examples of top-level leaderships’ role to sound HSI and SE practices. From a SE standpoint, the Air Force set formal requirements and expected product trade studies based on HSI concerns. At the program’s outset Air Force leadership set clear supportability goals, explained their intent, and funded programs to show prime contract engineers actual Air Force maintenance conditions.

Pratt & Whitney embraced processes that supported sound HSI outcomes and included diverse disciplines in major design and configuration decisions. Pratt & Whitney leadership invested in mock-ups, conducted testing, and held engineers accountable for RM&S standards, all of which led to HSI success. These combined efforts of customer and contractor to define clear requirements and communicate common expectations led to success.

The efforts described above can be summarized into several key HSI success factors:

1. Air Force policy to elevate HSI early in acquisition and development.

2. Design and trade studies that included HSI domains and cross-domain integration.
3. HSI's early inclusion in the contractor's SE methodology.
4. Participation with Air Force maintainers to understand their practices and challenges.

Insights into HSI's success in this case study:

1. The Air Force put their desired outcome into practice via formal HSI deliverables and requirements.
2. The IPD teams engaged HSI domain expertise in system design and the CCBs ensured multi-disciplinary management oversight. (IPD teams are more recently referred to as IPTs, now a hallmark of sound SE practice.)
3. Pratt & Whitney's early commitment to embrace HSI in their SE and project management practices defined the system from concept through flight test.

Resources

- "Cost Estimation of Human Systems Integration," Kevin K. Liu, Masters of Science thesis at Massachusetts Institute of Technology [MIT], June, 2010

—Modified from Human Systems Integration Practitioner's Guide (2015) by Tanya Andrews (MSFC)

D.7 Inadequate Training, Procedures, Interface Design and Fatigue: The Collision Between Navy Destroyer John S. McCain and Tanker Alnic MC

Abstract

On August 21, 2017, the U.S. Navy destroyer John S. McCain collided with the tanker Alnic MC. The McCain was overtaking the Alnic in the westbound lane of the Singapore Strait Traffic Separation Scheme when the destroyer had a perceived loss of steering. While the crew attempted to regain control of the vessel, the McCain unintentionally turned to port, into the Alnic's path. As a result of the collision, 10 McCain sailors died, 48 were injured, and the vessel sustained over $100 million in damage. The National Transportation Safety Board (NTSB) concluded that the probable cause of the accident was lack of effective operational oversight by the Navy, which resulted in insufficient training and inadequate bridge operating procedures. The NTSB also noted that design of the steering and thrust control system contributed to the collision.

> **HSI comment**: Design of the Integrated Bridge and Navigation System (IBNS) was not tolerant to operational errors.

Background

As the McCain entered the Singapore Strait Traffic Separation Scheme, steering and thrust were being controlled by the helmsman from the helm station. The commanding officer directed that the lee helm station be manned to control thrust, because he anticipated that the helmsman would be heavily tasked with steering. Thrust for the propeller shafts was successfully transferred from the helm to the lee helm station. However, steering control was also unintentionally shifted to the lee helm station.

Shortly after the transfer, the helmsman reported a loss of steering. Although the touch-screen displays for both stations would have indicated that the lee helm station had control of steering, the helmsman, lee helmsman, and watch overseer did not recognize that control had been transferred. Unable to control the rudders from his station, the helmsman perceived that steering control had been lost.

> **HSI comment**: The IBNS display design did not adequately support system status recognition. Neither mission design nor training prepared the crew for error catching.

Prior to the unintentional transfer of steering control, the McCain helmsman had been using up to 5 degrees of starboard rudder to maintain the ship's ordered heading of 230 degrees. The rudders immediately shifted to 0 degrees once the lee helm station took control, as designed for stations without a physical steering wheel. In addition, prior to the transfer of thrust control from the helm to the lee helm station, the throttles controlling the propeller pitch and rpm had been paired so that the actuation of one throttle also moved the other throttle to the same position.

> **HSI comment:** While the crew were able to begin executing a recovery, delays in recognizing and responding to the situation resulted in insufficient time for their actions to prevent the mishap.

During the transfer of thrust control, the system automatically unpaired the throttles, because the process for shifting control required each throttle to be transferred independently. When ordered to slow the ship to 10 knots, the lee helmsman reduced port thrust, assuming starboard thrust would follow, because he believed the throttles were paired. The throttles thus became unintentionally mismatched, with the starboard propeller providing greater thrust.

> **HSI comment**: Training and procedures did not ensure that crew understood basic IBNS operation. The design required additional unnecessary steps for basic operations.

Displays showing that the throttles were mismatched were visible from almost anywhere on the bridge. During the accident sequence, the throttles remained mismatched for over a minute, but no one on the bridge recognized the lee helmsman's error, and, consequently, no actions were taken to correct it. The mismatched throttles resulted in an accelerated rate of turn to port toward the Alnic.

> **HSI comment:** Design of the IBNS display did not adequately support recognition of system status. Neither mission design nor training adequately prepared the crew for error catching.

While the McCain crew was attempting to regain control of steering, the control location shifted from the lee helm, to aft steering, to the helm, and back to aft steering. An analysis of the track of the McCain shows decreasing speed and an increasing rate of turn to port until, just seconds before the collision, the destroyer's heading began to shift to starboard. The throttles were matched about 36 seconds before the collision, and aft steering watchstanders brought the rudders to 15 degrees to starboard about 16 seconds prior, but these actions were too late to prevent the accident.

The McCain lee helmsman did not sleep during the night prior to the accident, and the majority of the bridge crew had 5 hours or less sleep. The accident occurred during a time period considered to be a circadian low (roughly 0200–0600), when the body is normally more fatigued and prone to diminished alertness and degraded performance. Additionally, the ship was operating under a watch schedule that shifted each 24-hour period, resulting in crew sleep periods that were continually changing.

> **HSI comment:** The crew's sleep and watch schedules contributed to having personnel that were not able to perform at their best, increasing the likelihood of crew performance errors.

Official HSI Findings & Recommendations

The NTSB found that:

- The Navy failed to provide effective oversight in the areas of bridge operating procedures, crew training, and fatigue mitigation.
- The steering and thrust control written operating procedures on the bridge did not describe the actions needed to transfer control between stations and therefore were inadequate.
- Training on the operation of the Integrated Bridge and Navigation System was inadequate, because it did not ensure that the crew could perform the basic functions of the watch, such as the transfer of steering and thrust control between bridge stations.
- Bridge crewmembers were acutely fatigued at the time of the accident, which impacted their ability to recognize and respond to the situation.

- The design of the touch-screen steering and thrust control system increased the likelihood of the operator errors that led to the collision.
- The transfer of thrust control independently for each propeller shaft was unnecessarily complex
- The touch-screen throttle controls deprived the lee helmsman of tactile feedback when the throttles were unpaired and mismatched.

The NTSB recommended that the Navy:

- Ensure that the modernization of complex systems incorporates the design principles set forth in ASTM International Standard F1166, Standard Practice for Human Engineering Design for Marine Systems, Equipment, and Facilities.
- Revise written instructions for bridge watchstanders to include operating procedures for shifting steering and thrust control between all bridge stations; provide a description of and procedures for pairing and unpairing throttles; and ensure that revised technical manuals are distributed to all relevant ships.
- Revise the training standards for relevant bridge crew to require demonstrated proficiency in all system functions.
- Institute Seafarers' Training, Certification and Watchkeeping Code rest standards for all crewmembers aboard its vessels.

HSI Takeaways

- Thorough and early inclusion of HSI in development and modernization of complex systems could have decreased the likelihood of a fatal and costly accident.
- Proper application of HSI standards and practices can enable:
  - The design of hardware, software, and procedures that tolerate and enable recovery from errors;
  - Development of training programs that provide personnel with the requisite knowledge, skills, and abilities to properly operate, maintain, and support the system;
  - Establishment of mission architectures and parameters designed to sustain personnel effectiveness across the mission.

Resources

- https://www.ntsb.gov/investigations/AccidentReports/Reports/MAR1901.pdf

—Contributed by Jon Holbrook (LaRC)

D.8 The Cost of Untested Assumptions About Human Performance: The Case of the B737MAX

In March of 2019, Boeing Aircraft newest model, the B737MAX, was grounded all over the world following two fatal accidents, one in Indonesia and one in Ethiopia. Across these accidents, 346 passengers and crew lost their lives. The accidents resulted from the flight crews' inability to overcome the erroneous activation of the Maneuvering Characteristics Augmentation System (MCAS). The MCAS was intended to mimic flight pitching behavior of the previous B737NG model. In both crashes, MCAS was automatically activated by a false input from a damaged angle-of-attack sensor.

The grounding of the Boeing 737MAX was unprecedented on multiple dimensions. In the history of aircraft grounding by the Federal Aviation Administration (FAA), there are two prior cases: the grounding of the DC10 in 1979 and the grounding of the B787 in 2013. The DC10 was grounded after American Airlines flight 191 crashed on departure from Chicago O'Hare airport following the separation of the left engine. The B787 was grounded following several cases of thermal runaway of its lithium-ion batteries leading to fires. Both cases were considered mechanical issues (though the separation of the engine on the DC10 was later found to have been caused by an improper maintenance procedure (NTSB, 1979)). The grounding of the B737MAX, however, was the first time such grounding resulted from flight crew interaction with aircraft systems.

It is also the case that the DC10 was grounded for two months, the B787 was grounded for three months, and at the time of this writing, although no longer officially grounded in the US, there are no B737MAX flying in revenue service yet two years after it was grounded. As can be imagined, the cost of the grounding of the B737MAX far exceeds that of the previous cases. In addition to the incalculable costs to the 346 victims and their loved ones due to these accidents, the subsequent grounding of the B737MAX has incurred a huge cost to the US economy, including to a long supply chain, to the airlines, and of course to the aircraft manufacturer, Boeing. Beyond the direct monetary cost, there have been many jobs lost, confidence in the aircraft and in Boeing lost, and trust in the FAA as the certification authority lost.

According to international agreements, the aircraft state of design is responsible for determining that the design is safe and that the aircraft is airworthy. Most countries in the world do not have the resources or the capability to independently validate aircraft certification and so simply accept the certification done by the authorities of the state of design. The FAA has long been esteemed in all things aviation, including aircraft certification. The grounding of the B737MAX, especially the fact that the aircraft was first grounded by civil aviation authorities of other countries and the FAA was, in fact, the last authority to ground the aircraft, severely damaged the reputation of the FAA and its accepted authority. This damage can be seen in the fact that when the FAA decided that the B737MAX can be returned to service (pending some specific maintenance activities and crew training) in November of 2020, the civil aviation authorities of Europe, Canada, and of China decided to impose additional requirements and delay their lifting of the grounding orders. Civil aviation authorities of many countries around the world were waiting for these authorities to make their final decision before lifting their own grounding orders.

Following the grounding of the B737MAX, the FAA convened a team of experts from nine foreign civil aviation authorities and from NASA to review the certification process of the B737MAX flight control system and make recommendations on how that process could be improved. The Joint Authorities Technical Review (JATR) team identified a number of assumptions made during the design, development and certification of the aircraft concerning human performance, and noted that these assumptions were often not tested or validated, and were just accepted. One such assumption had to do with pilot reaction time.

HSI Findings & Recommendations

With respect to pilot's reaction time, the JATR team made these observations and findings:

- Observation O2.8-A: FAA guidance for test flights in AC 25-7D, Flight Test Guide for Certification of Transport Category Airplanes, and AC 25.1329-1C, Approval of Flight Guidance Systems, require test pilots to delay initiation of response to flight control or flight guidance malfunctions to account for pilot recognition time and pilot reaction time. Often, recognition time is assumed to be 1 second, and reaction time is assumed to be 3 seconds. Thus, test pilots are told that "Recovery action should not be initiated until 3 seconds after the recognition point" (AC 25.1329-1C).
- Observation O2.8-B: The current guidance recognizes that pilot recognition time may depend on various factors including the nature of the failure, but applicants are only required to prepare specific justification of their assumed recognition time if it is less than 1 second.
- Observation O2.8-C: Although the above guidance is aimed at test pilots conducting test flights, applicants seem to use this guidance as a design assumption that the pilot will be able to respond correctly within 4 seconds of the occurrence of a malfunction. For example, in the case of the B737 MAX, it was assumed that, since MCAS activation rate is 0.27 degrees of horizontal stabilizer movement per second, during the 4 seconds that it would take a pilot to respond to an erroneous activation, the stabilizer will only move a little over 1 degree, which should not create a problem for the pilot to overcome.
- Observation O2.8-D: No studies were found that substantiate the FAA guidance concerning pilot recognition time and pilot reaction time.
- Observation O2.8-E: Several FAA studies with general aviation pilots demonstrate that these pilots may take many seconds, and in some cases many minutes, to recognize and respond to

malfunctions (e.g., DOT/FAA/AM-97/24; DOT/FAA/AM-02/19; DOT/FAA/AM-05/23).

- Observation O2.8-F: A NASA study of abnormal flight events with qualified, current, and active airline pilots also found substantially longer recognition times and reactions times, even in the case of expected events, than the times given in AC 25-7D and AC 25.1329-1C (Casner, Geven, & Williams, 2013).
- Observation O2.8-G: Analysis of aviation accidents demonstrates that pilots may take a significantly longer time to recognize a malfunction and respond to it than the test flight guidance suggests. For example, the NTSB states: "When a flight crew is confronted with a sudden, abnormal event, responses are more likely to be delayed or inappropriate." (NTSB/AAR-14/01)
- Observation O2.8-H: Modern aircraft can have subtle failure modes that may take substantial amounts of time to be recognized. Furthermore, automation can mask some failures and significantly delay the possibility for the pilot to recognize the malfunction.
- Finding F2.8-A: It is not clear on what the FAA guidance concerning pilot recognition time and pilot reaction time is based.
- Finding F2.8-B: Pilot recognition time and reaction time to a malfunction may depend on the nature of the malfunction, the circumstances under which it occurs, the corrective action required, and the individual pilot.
- Finding F2.8-C: There is a substantial difference between the situation of a test pilot who is testing a particular malfunction with precise foreknowledge of the malfunction to be tested and the proper response to be initiated, and the situation of a line pilot on a routine revenue flight who is not expecting any malfunction. Thus, guidance that is relevant to test flights may not be appropriate for routine revenue flights.
- Finding F2.8-D: The 3-second reaction time assumption dates back decades, when autopilot performance was constantly monitored by the crew in flight (e.g., guidance given in AC 25.1329-1A, Automatic Pilot Systems Approval, dated July 8, 1968). However, with increasing reliability and advances in flight deck alerting and displays, it may no longer be appropriate to assume that the pilot flying will be monitoring the automation as closely as in the past.
- Finding F2.8-E: The FAA's guidance concerning pilot reaction time of 3 seconds may not be appropriate given current aircraft technology and the current operational environment.
- Finding F2.8-F: Although current guidance seems to recognize potential variability in pilot recognition time, it is not clear that applicants are following the spirit of that guidance, because only recognition times of less than 1 second must be formally justified.

Given these observations and findings, the JATR team made the following recommendation:

- Recommendation R2.8: The FAA should establish appropriate pilot recognition and reaction times, based on substantive scientific studies which take into account the operational environment, circumstances, and the effect of surprise.

In summary, the JATR team included the following general statement about Human System Integration in the aircraft certification process:

- Humans design, build, maintain, and operate every part of the global aviation system. The enviable safety record of the aviation system is a direct result of human capabilities. At the same time, all aviation accidents are the result of human limitations. This is not to say that all accidents are the result of human error, but of human limitations, such as limitations to people's imagination and their ability to foresee, predict, and anticipate possible situations. As the technology becomes more advanced, and as the operational environment becomes more complex, understanding the scope and nature of the interactions between the technology, the human, and the environment becomes more critical to aviation safety. This criticality of human factors to aviation safety has been recognized and has been codified in various rules such as 14 CFR §§ 25.1302 (Installed Systems and Equipment for Use by the Flightcrew), 25.1309 (Equipment, Systems, and Installations), and 25.1322 (Flightcrew Alerting). While issues in human-machine interaction are at the core of all recent aviation accidents and are implicated in the two B737 MAX accidents, the FAA has very few human factors and human system integration experts on its certification staff. The JATR team identified multiple human factors related issues in the certification process. Because human factors is a cross-cutting aspect, related recommendations are made under several of the different areas identified in this summary.

The JATR team followed this statement with a recommendation:

- Recommendation R7: Based on the JATR team's observations and findings related to human factors-related issues in the certification process, JATR team members recommend that the FAA integrate and emphasize human factors and human system integration throughout its certification process. Human factors-relevant policies and guidance should be expanded and clarified, and compliance with such regulatory requirements as 14 CFR §§ 25.1302 (Installed Systems and Equipment for Use by the Flight crew), 25.1309 (Equipment, Systems, and Installations), and 25.1322 (Flight crew Alerting) should be thoroughly verified and documented. To enable the thorough analysis and verification of compliance, the FAA should expand its aircraft certification resources in human factors and in human system integration.

The consequences of the B737MAX mishaps were not limited to the accidents themselves. First and foremost 346 people lost their lives, and the cost to them and their loved ones cannot be overstated. The resultant grounding of the B737MAX worldwide has resulted in ongoing financial costs that merely add to the consequences in human life and suffering. Boeing's out-of-pocket expenses around the grounding of the B737MAX are estimated to go well beyond 20 billion dollars. The various court and legal settlements will take time to resolve as well as compensation for airline losses, costs of retrofitting existing aircraft, and modifying production lines. It is estimated that the development of a completely new aircraft costs about 10 billion dollars and that the cost of developing a model variant is about 2 billion dollars. The B737MAX is a variant of the B737-800 (B737NG). Thus, the direct cost of the grounding to Boeing may well exceed 10 times the cost of the original development of the B737MAX, and be twice as much as it would have cost the company to develop a completely new aircraft model. It is impossible to estimate the significant long-term monetary, social and political cost of damage to reputation and of the international loss of confidence in the FAA's aircraft certification process.

HSI Takeaways

- It is cheaper to properly integrate HSI considerations in design and testing than to compensate for deficiencies during operations.
- Design assumptions about human performance should be carefully articulated, documented, and validated through HITL testing with a representative sample of users/operators/ maintainers.
- Test like you fly – Boeing aircraft are being flown all over the world with pilots of varying levels of experience and knowledge, not just by Boeing or FAA Test Pilots.

Resources

- Casner, S.M., R.W. Geven, and K.T. Williams (2013). The Effectiveness of Airline Pilot Training for Abnormal Events. Human Factors, 55, 477-485.
- DOT/FAA/AM-97/24. Beringer, D.B., and Harris, H.C. Jr. (1997). Automation in general aviation: Two studies of pilot responses to automation malfunctions. US Department of Transportation, Federal Aviation Administration, Office of Aerospace Medicine, Washington, DC.
- DOT/FAA/AM-02/19. Roy, K.M. and Beringer, D.B. (2002). General aviation pilot performance following unannounced in-flight loss of vacuum system and associated instruments in simulated instrument meteorological conditions. US Department of Transportation, Federal Aviation Administration, Office of Aerospace Medicine, Washington, DC.
- DOT/FAA/AM-05/23. Beringer, D.B., Ball, J.D., and Brennan, K. (2005). Comparison of a typical

electronic attitude-direction indicator with terrain-depicting primary flight display for performing recoveries from unknown attitudes: Using difference and equivalence tests. US Department of Transportation, Federal Aviation Administration, Office of Aerospace Medicine, Washington, DC.

- The JATR's final submission to the FAA can be found at: https://www.faa.gov/news/media/attachments/Final_JATR_Submittal_to_FAA_Oct_2019.pdf
- NTSB, 1979. Aircraft Accident Report – American Airlines, Inc. DC-10-10, N110AA, Chicago-O'Hare International Airport Chicago, Illinois, May 25 1979. NTSB-AAR-79-17. National Transportation Safety Board, Washington, D.C.
- NTSB/AAR-14/01. Descent Below Visual Glidepath and Impact with Seawall, Asiana Airlines Flight 214, Boeing 777-200ER, HL7742, San Francisco, California, July 6, 2013. National Transportation Safety Board, Washington, DC.
- The Seattle Times: https://www.seattletimes.com/tag/737-max/

—*Contributed by Immanuel Barshi (ARC)*

Appendix E. HSI Tools

General HSI			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Searchable HSI Tool Catalog	HSI Tools Catalog	DoD with Alion Science	https://hsitools.alionscience.com/
DoD Searchable HSI Tool Catalog	HSI Tools Catalog	DoD	https://www.dau.edu/cop/hsi/Lists/Tools/AllItems.aspx
Concept Development			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Concept mapping	Cmap	Institute for Human and Machine Cognition	https://cmap.ihmc.us/
Diagramming	Visio	Microsoft	https://www.microsoft.com/en/microsoft-365/visio/flowchart-software
Prototyping	Axure RP 9	Axure Software Solutions	https://www.axure.com/
Prototyping	Figma	Figma	https://www.figma.com/
Prototyping	MS Maquette	Microsoft	https://www.maquette.ms/
Prototyping	Sketch	Sketch B.V.	https://www.sketch.com/
Sketching	Concepts	TopHatch, Inc.	https://tophatch.com/
Sketching	Scapple	Literature & Latte Ltd.	https://www.literatureandlatte.com/scapple/overview
Storyboarding	Storyboarder	Wonder Unit, Inc.	https://wonderunit.com/storyboarder/
Vector graphics	Affinity Designer	Serif, Ltd.	https://affinity.serif.com/en-us/
Design Tools			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
3D Printing	PreForm	Formlabs	https://formlabs.com/software/
3D Printing	Simplify 3D	Simplify 3D	https://www.simplify3d.com/
Computer Aided Design	AutoCAD	Autodesk	https://www.autodesk.com/products/autocad/overview?term=1-YEAR&support=null

Computer Aided Design	Creo Parametric & Creo View	PTC Technology	https://www.ptc.com/en/products/creo/parametric
Computer Aided Design	Sketchup	Trimble	https://www.sketchup.com/
Finite Element Modeling	LS-DYNA	Livermore Software Technology	http://www.lstc.com/products/ls-dyna
Fluid Structure Interaction Simulations	ADINA	Adina R&D, Inc.	http://www.adina.com/
Graphical Design	Blender	Blender Foundation	https://www.blender.org/
Graphical Design	Cinema 4D	Maxon	https://www.maxon.net/en/cinema-4d
Graphical Design	Creative Cloud	Adobe	https://creativecloud.adobe.com/
Graphical Design	Figma	Figma	https://www.figma.com/
Graphical Design	Gravity Sketch	Horizon 2020 Programme of the EU	https://www.gravitysketch.com/
Graphical Design	LightWave	NewTek, Inc.	https://www.lightwave3d.com/
Graphical Design	Modo	The Foundry Visionmongers Limited	https://www.foundry.com/products/modo
Graphical Design	Procreate	Procreate	https://procreate.art/
Graphical Design	Rhino	Robert McNeel & Associates	https://www.rhino3d.com/
Graphical Design	Unity	Unity Technologies	https://unity.com/
Integrated Development Environment	Qt Creator	The Qt Company	https://www.qt.io/product/development-tools
Model Based System Engineering	Magic Draw	No Magic, Inc.	https://www.nomagic.com/products/magicdraw
Multibody Dynamics Simulations	ADAMS	MSC Software	https://www.mscsoftware.com/product/adams
Structural Design	MIDAS GEN	MIDASoft	https://www.midasoft.com/
HITL Testing			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Animation	Maya	Autodesk	https://www.autodesk.com/products/maya/overview?term=1-YEAR&support=null
Animation	Vyond	GoAnimate, Inc.	https://www.vyond.com/
Experience Management	Qualtrics XM	Qualtrics	https://www.qualtrics.com/

Eye Tracking	COBRA	NeuroFit, Inc.	https://neurofit.tech/cobra
Eye Tracking	HTC Vive Pro Eye	HTC Corporation	https://www.vive.com/eu/product/vive-pro-eye/overview/
Eye Tracking	Tobii Pro Glasses	Tobii Pro	https://www.tobiipro.com/product-listing/tobii-pro-glasses-3/
Eye Tracking	Tobii Pro Lab	Tobii Pro	https://www.tobiipro.com/product-listing/tobii-pro-lab/
Habitability Observation Survey	iSHORT	NASA Johnson Space Center	https://apps.apple.com/us/app/ishort/id1489223302
Survey Tools	LimeSurvey	LimeSurvey GmbH	https://www.limesurvey.org/
Survey Tools	Survey Crafter	Survey Crafter, Inc.	https://www.surveycrafter.com/interim2/default.asp
Survey Tools	SurveyMonkey	SurveyMonkey	https://www.surveymonkey.com/
Task Load Index Survey	NASA TLX	NASA Ames Research Center	https://humansystems.arc.nasa.gov/groups/TLX/
Video Editing	Blackbird	Blackbird, PLC	https://www.blackbird.video/
Visualization	Camtasia	TechSmith	https://www.techsmith.com/video-editor.html
Visualization	Davinci Resolve	Black Magic Design	https://www.blackmagicdesign.com/products/davinciresolve/
Visualization	HTC Vive Virtual Reality System	HTC Corporation	https://www.vive.com/us/
Visualization	Improov	Middle VR	https://www.improovr.com/home-v2/
Visualization	Media Entertainment Collection	Autodesk	https://www.autodesk.com/collections/media-entertainment/overview?term=1-YEAR&support=null
Visualization	Mixed Reality Toolkit 2	Opensource Collaboration	https://microsoft.github.io/MixedRealityToolkit-Unity/README.html
Visualization	Oculus Rift	Facebook Technologies, LLC	https://www.oculus.com/
Visualization	Tableau	Tableau Software, LLC	https://www.tableau.com/
Visualization	Unity	Unity Technologies	https://unity.com/
Usability Testing	Morae	TechSmith	https://www.techsmith.com/tutorial-morae.html

Operational Monitoring			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Cardiac Monitoring	Bittium Faros	Bittium	https://www.bittium.com/medical/bittium-faros
Data Collection Software	LabVIEW	National Instruments	https://www.ni.com/en-us/shop/labview.html
Electrophysiology Data Processing	EEGLab	Swartz Center for Computational Neuroscience	https://sccn.ucsd.edu/eeglab/index.php
Fine Motor Performance Assessment	Fine Motor Skills Test Battery	NASA Ames Research Center	https://software.nasa.gov/software/MSC-26032-1
Heart Rate Monitoring	Polar H10	Polar	https://www.polar.com/us-en/products/accessories/h10_heart_rate_sensor
Neurocognitive Assessment	Cognition	University of Pennsylvania	https://techport.nasa.gov/view/23228
Performance and Workload Assessment	Multi-Attribute Task Battery-II	NASA Langley Research Center	https://matb.larc.nasa.gov/
Physiological Monitoring	Eyes Dx & MAPPS	Eyes Dx	https://www.eyesdx.com/
Problem Reporting	Mission Assurance System	NASA Ames Research Center	https://sma.nasa.gov/news/articles/newsitem/2014/04/23/ames-research-center-s-mas-platform-is-used-by-iss
Psychology Test Battery Development	Psychology Experiment Building Language (PEBL)	Source Forge	http://pebl.sourceforge.net/
Stenography Software	DigitalCAT	Stenovations	https://www.stenovations.com/digitalcat/
Human Factors Engineering			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Biomechanical Modeling	OpenSim	Stanford University	https://simtk.org/projects/opensim
Fatigue Risk	Aviation Fatigue Meter	Pulsar Informatics	https://pulsarinformatics.com/products/aviation
Fatigue Risk	Fatigue Avoidance Scheduling Tool (FAST)	Fatigue Science	https://www.fatiguescience.com/fast-scheduling/
Hand Tracking	Leap Motion	Ultraleap, Ltd	https://developer.leapmotion.com/
Human Modeling	Jack	Siemens	https://web.archive.org/web/20161202165106/http://www.plm.automation.siemens.com/en_us/products/tecnomatix/manufacturing-simulation/human-ergonomics/jack.shtml

Human Modeling	Process Simulate Human	Siemens	https://www.dex.siemens.com/plm/tecnomatix/process-simulate-human
Motion Capture	Kinect	Microsoft	https://developer.microsoft.com/en-us/windows/kinect/
Motion Capture	Shogun	Vicon	https://www.vicon.com/software/shogun/
Motion Capture	XSENS MVN Analyze	Xsens	https://www.xsens.com/products
Workflow Management	Micro Saint	Alion Science and Technology	http://www.microsaintsharp.com/
Workflow Management	Unreal Engine	Epic Games, Inc.	https://www.unrealengine.com/en-US/
Task Analysis	Behavioral Observation Research Interactive Software (BORIS)	Universita Degli Studi Di Torino	http://www.boris.unito.it/
Task Analysis	Blackbird	Blackbird, PLC	https://www.blackbird.video/
Task Analysis	IMPRINT	U.S. Army	https://www.dac.ccdc.army.mil/HPM_IMPRINT.html
Task Analysis	MindManager	Corel Corp	https://www.mindmanager.com/en/
Task Analysis	Task Architect	Task Architect	https://www.taskarchitect.com/
Maintainability and Supportability			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Workflow Automation	Camunda	Camunda	https://camunda.com/

Habitability and Environment			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Acoustics & Vibration	COMSOL Multiphysics Software	COMSOL Inc.	https://www.comsol.com/
Acoustics & Vibration	VA One	ESI Group	https://www.esi-group.com/products/vibro-acoustics
Acoustics & Vibration	Wave6	Dassault Systemes	https://www.3ds.com/products-services/simulia/products/wave6/
Dynamic loading	Human Body Models	Global Human Body Models Consortium (GHBMC)	http://www.ghbmc.com/
Lighting Simulations	Adaptive Lighting for Alertness (ALFA)	Solemma	https://www.solemma.com/Alfa.html
Lighting Simulations	Optics Studio	Zemax	https://www.zemax.com/products/opticstudio
Lighting Simulations	Radiance	Lawerence Berkeley National Lab	https://www.radiance-online.org/
Radiation	NASA Space Weather	NASA Goddard Space Flight Center	https://play.google.com/store/apps/details?id=gov.nasa.gsfc.iswa.NASASpaceWeatherApp&hl=en_US&gl=US

Training			
Tool Use	**Tool Name**	**Developed By**	**Additional Information**
Flight Simulation	DAVE-ML	AIAA Modeling and Simulation Technical Committee	https://daveml.org/
Flight Simulation	Flight Simulator	Microsoft	https://www.xbox.com/en-US/games/microsoft-flight-simulator
Flight Simulation	X-Plane 11	X-Plane	https://www.x-plane.com/
Training Platform	Captivate	Adobe	https://www.adobe.com/products/captivate.html
Training Simulation	Multi-Aircraft Control System (MACS)	NASA Ames Research Center	https://hsi.arc.nasa.gov/groups/aol/technologies/macs.php

Appendix F. HSI Data Requirements Description Examples

DRD examples included in this section can be tailored for specific project needs and mission types. Most have been used with commercial partners in Human Exploration Programs. Additionally, multiple examples in a few of the categories below have been provided within this Appendix for reference and tailoring. Additional helpful information on DoD resources on acquisition data item descriptions can be found in Appendix G, Resources.

F.1 Acoustic Noise Control Plan

1. DESCRIPTION/USE:
The ANCP documents the approach of the system design and development to ensure compliance with the system-level acoustic requirements. Plan must identify significant noise sources and challenges and be updated iteratively to include the results of current testing, analyses, and noise control mitigation strategies and efforts.
2. INITIAL SUBMISSION:
Prior to PDR
3. SUBMISSION FREQUENCY:
Updates to the ANCP must be provided at major design milestones including but not limited to the critical design review (CDR) and with applicable verification test plans and closure notices (VCNs).
4. REMARKS:
Early development testing is required as part of the ANCP, to be used in analyses for development of noise controls. Contractor may reference NASA/TP-2014-218556 Human Integration Design Processes (HIDP) for additional ANCP guidance.
5. DATA PREPARATION INFORMATION:
a. SCOPE:
The ANCP includes the schedule for completing acoustic milestones, applicable system-level acoustic requirements that are agreed to at the System Requirements Review (SRR), sub-allocation of the system-level acoustic requirements to individual components, subsystems and integrated hardware, identification and rationale for selection of noise-producing components, development of noise control mitigation efforts at the component, subsystem and system levels, development of an integrated system-level acoustic analysis method or model, acoustic testing and analyses results, and remedial actions.
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
1. Project Planning - Acoustic milestones included in system schedule, including but not limited to: a. Component/subsystem acoustic testing and selection b. Development of a system-level integrated acoustic analysis method or model c. Component, subsystem, and system-level acoustic verification tests d. Remedial efforts following acoustic verification tests 2. Identification of applicable acoustic requirements a. System-level requirements b. Sub-allocation of system-level requirements to subsystems (e.g. ECLSS), components (e.g., cabin fan), and integrated hardware (e.g., power supply) 3. Identification of noise-producing components/hardware and noise-transmission paths in subsystem/system

a. Trade study to determine quietest options for performance needs and rationale for selection b. Individual component/hardware testing of prototypes and engineering units (Components/hardware must be operated with flight-like load (e.g., backpressure on fans)) c. Acoustic analysis to determine integrated acoustic levels compared to system-level requirement 4. Noise control design a. Component level noise control mitigations (e.g., mufflers for fans, vibration isolation for pumps, etc.) b. Subsystem and system-level noise control mitigations (e.g., duct treatments, close-outs, etc.) c. Iterative acoustic testing of components and subsystems with noise control mitigations d. Acoustic analyses of system-level noise control mitigations 5. Development or refinement of system-level analytical method or model to determine the effects of additional hardware, ORUs, and microgravity effects 6. Acoustic verification by test of components, subsystems, and system a. Procedures b. Results c. Validation of system-level integrated analysis or model d. Remedial actions, if necessary (e.g., fan speed adjustments, additional noise control mitigations)
6. FORMAT
Searchable electronic file. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining”.

F.2 Anthropometric Analysis

1. **DESCRIPTION/USE:**
The Anthropometric Analysis DRD is intended to provide NASA with insight into the system developers' design to ensure crew interfaces extend to the entire anticipated crew population and considers worst-case scenarios. It is anticipated that this DRD will be fulfilled by artifacts needed by the provider in the normal course of design and development. The purpose of the design requirements is to ensure that all vehicle, vehicle-suit hardware, and interfaces are operable by the entire anticipated crew population. NASA requires and expects that all crewmembers are provided with hardware that they can handle, operate, and use for mission success and crew safety. Thus, it is necessary that the designers and developers show by means of analysis, modeling, and physical testing, each design against the anthropometric requirements. Anthropometric analysis may consist of defining test subjects based on a percentile analysis, comparing to the extremes of the expected population, or comparing hardware dimensions with a large sample from a population data set of potential users. For tests with small sample sizes, anthropometric analysis is used to prove the design meets the entire population range. Whichever approach is used, the end result is quantification of subject accommodation for the purposes of compliance evaluation. No one-size-fits-all anthropometric analysis method applies to all situations; therefore, it is important to select a method that is appropriate to the problem being solved. The evaluation of designs is a multiphase process that depends on the stages of the design life cycle. In the preliminary stages of design, robust analytical and computer-aided design (CAD) modeling should be used at a minimum, to identify the worst-case scenarios and the critical dimensions of interest, and to determine accommodation of the design. The assumptions of posture, suit effects, and other human interface variables must be documented so they can be verified with future Human-in-the-Loop (HITL) testing. HITL testing will either validate those assumptions or disprove them. If the assumptions are disproven, the analytical and CAD modeling work can be reanalyzed with the corrected information and the design can be iteratively analyzed and verified using HITL testing. As the design matures within the design cycle, the evaluation of the design against the selected anthropometric data set must move from the theoretical to the physical using HITL testing. Anthropometric Analysis is described in Section 4.5.2 Design for Anthropometry of NASA/TP-2014-218557 Human Integration Design Processes (HIDP) and Section 4 Anthropometry, Biomechanics, and Strength of NASA/SP-2010-3407 Human Integration design Handbook (HIDH).
2. **INITIAL SUBMISSION:**
Prior to PDR
3. **SUBMISSION FREQUENCY:**
Updates submitted prior to PDR and CDR, submitted with HITL test reports, and with Verification Closure Notice (VCN).
4. **REMARKS:**
5. **DATA PREPARATION INFORMATION:**
a. SCOPE:

The Anthropometric Analysis will evaluate tasks as identified in TBR Task Analysis as demonstrating edge cases for critical dimensions.

b. APPLICABLE DOCUMENTS:

c. CONTENTS:

Artifacts for the Anthropometric Analysis DRD should contain but are not limited to the following information per the milestone schedule below:

Milestone	Minimum Delivery
Prior to PDR	• Defined critical dimensions, based on DRD-HSR-001 Task Analysis and DRD-HSR-002 Worksite Analysis, with any limitations and assumptions addressed. • Preliminary analyses (analytical, modeling, and HITL) toward proving that the concept designs meet the anthropometric requirements, with any limitations and assumptions addressed. • Plans for mitigation efforts if analyses indicate that design does not meet requirements • Plan for verification of requirements
Prior to CDR	• Define HITL testing to examine the impact of anthropometric requirements on the design; • Updated analyses (analytical and modeling) based on results of HITL testing to examine the impact of anthropometric requirements on the human systems interface design. • Plans for mitigation efforts if analyses indicate that design does not meet requirements • Final plans for anthropometric verification testing
30 days post completion of relevant HITL Testing, updated modeling, or updated anthropometric analysis.	• Updated analyses (analytical and modeling) based on results of HITL testing, updated modeling, or updated anthropometric analysis to examine the impact of anthropometric requirements on the human systems interface design. • Plans for mitigation efforts if analyses indicate that design does not meet requirements

	• Updates for anthropometric verification testing
VCN	• Demonstration of adherence to HMTA 02 and approved justification for lack of compliance. • All testing completed and mitigation efforts incorporated into the design

6. **FORMAT**

Electronic file that is searchable. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining”.

F.3 Crew Operating Loads Analysis

1. DESCRIPTION/USE:
The Crew Operational Loads Report DRD is intended to provide NASA with insight into the system developers' design to ensure crew interfaces extend to the entire anticipated crew population and considers worst-case crew load scenarios. It is anticipated that this DRD will be fulfilled by artifacts needed by the provider in the normal course of design and development. Process and analysis methods are described in Section 4.5.4 Design for Strength of NASA/TP-2014-218557 Human Integration Design Processes (HIDP) and Section 4 Anthropometry, Biomechanics, and Strength of NASA/SP-2010-3407 Human Integration design Handbook (HIDH). The intent of this design process is to provide users with methodologies and best practices that should be implemented to ensure that adherence to the HSI requirements set forth by NASA with respect to strength is satisfactory. The hardware design should involve careful consideration for interactions between humans and interfaces when humans are performing tasks, including consideration for the weakest crewmember, hardware integrity, and performance decrements due to physiological adaptations to space flight. The reporting of human strength values should involve incorporation of worst-case scenarios as identified through careful selection of the data set and associated test conditions. These should be implemented to ensure the protection of all crewmembers, and of the hardware, vehicle, and mission completion. In the realm of human strength testing, worst-case scenarios manifest in the form of minimum values. Mean strength values can provide valuable information about the strength of a group of individuals, but do not provide end-users with information about the protection of weaker subjects (i.e., those with strength values lower than the mean). Inclusion of minimum strength values (i.e., strength values of the weakest individual) ensures that all other members of that tested population are able to effectively apply at least the force of the weakest subject. In sum, the reporting of minimum values provides users with guidelines for system design to protect the weakest crewmember who may operate a given hardware component or interface. Reporting maximum strength values for human-system interfaces provides users guidelines for protecting hardware from the strongest crewmembers who may operate a given hardware component or interface.
2. INITIAL SUBMISSION:
Prior to PDR
3. SUBMISSION FREQUENCY:
Updates submitted prior to PDR and CDR, submitted with Human-in-the-Loop (HITL) test reports, and submitted with Verification Closure Notice (VCN).
4. REMARKS:
5. DATA PREPARATION INFORMATION:
a. SCOPE:
Crew Operational Loads Analysis will evaluate tasks as identified through TBR Task Analysis and shall include EVA and IVA loads.

b. APPLICABLE DOCUMENTS:
c. CONTENTS:
At minimum, the Crew Operational Loads Report DRD shall contain the following information per the milestone schedule below: 1. Milestone Minimum Delivery 2. Prior to PDR: a. Defined posture and actions, based on DRD-085: Task Analysis and DRD-086: Worksite Analysis, with corresponding minimum and maximum strength values, criticality value, and any limitations and assumptions addressed. b. Preliminary CAD model work to prove that concept designs meet strength requirements and account for assumptions. c. Plan for verification of requirements. 3. Prior to CDR a. Updated postures and actions of tasks with corresponding minimum and maximum strength values, criticality value, and any limitations and assumptions addressed. b. CAD analysis, HITL developmental testing, and any hardware or additional testing or reports. c. Preliminary instrumented load tests performed to prove that concept designs meet strength requirements. d. Plans for mitigation efforts if analyses indicate that design does not meet requirements e. Final plan for verification of requirements. 4. 30 days post completion of relevant HITL Testing, updated modeling, or updated population analysis. a. Updated analysis based on load testing or hardware qualification reports. b. Updated analyses based on results of HITL testing to examine the impact of strength requirements on the human systems interface design. c. Plans for mitigation efforts if analyses indicate that design does not meet requirements. d. Updates for verification testing. 5. VCN a. Demonstration of adherence to HMTA 2 and approved justification for lack of compliance. b. All testing completed and mitigation efforts incorporated into the design
6. FORMAT
Searchable electronic document. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining”.

F.4 Crew Systems, Habitation, Utilization and Stowage System Data Book

1. DESCRIPTION/USE:
The purpose is to provide documentation of the crew systems, habitation accommodations, crew health accommodations, countermeasures interface, utilization and stowage design, analysis, performance, and verification for each element mission phase. This System Data Book evolves as the design matures and eventually documents all details of the system. It becomes a comprehensive source of information for all aspects of the Crew Systems, habitation, utilization and stowage design, analysis, test, performance, and verification. The customer shall use this data as the primary source to review and evaluate the design for approval to proceed to the next development phase.
2. INITIAL SUBMISSION:
See Attachment Submission Matrix
3. SUBMISSION FREQUENCY:
See Attachment Submission Matrix
4. REMARKS:
Documents referenced in the Data Book shall already be available to the purchasing agency or provided as an appendix or separate document.
5. DATA PREPARATION INFORMATION:
a. SCOPE: The System Data Book describes the crew systems, habitation accommodations, crew health accommodations, countermeasures interface, utilization and stowage requirements, derived requirements, design and analysis, design environments, interfaces, verification, performance, component limits and system architecture. b. APPLICABLE DOCUMENTS: c. CONTENTS: The Data Book shall include the following: Subsystem Overview: Provide a brief overview of subsystem definition including GFE provided hardware. Describe the crew systems, habitation accommodations, crew health accommodations, countermeasures interface, utilization and stowage design. Include aspects of the design such as the philosophical approach, the hardware selected, and the hardware heritage (previous flight experience), etc. Identify and describe the implementation of any new technologies. 1. **Requirements Overview:** Describe the driving requirements, derived requirements and available resources and/or limitations giving references to their origin. Describe the analysis or trade studies that yields the derived requirements. 2. **Detailed Design Description:** Describe the detailed design description, including hardware element description, hardware models, mass and volume properties, power and thermal profiles, schematic layouts, drawings and 3-D representations of components. In addition, include depictions of internal and external mechanical, electrical, thermal, software and human interfaces. Describe the consumables list, telemetry, data bandwidths, data storage, and system instrumentation. Provide a

summary of key trade studies that were performed to develop the design, technology readiness development plansand outcomes and status of the subsystem technical performance margins (TPMs). For the subsystem, also include the following:

- Crew information shall describe the logical flow and presentation of information on electronic displays that are design to support crew tasks. The analysis should include a clear description of displays including content, layout, display flow, navigation tools, display labeling and character sizes, use of color, use of icons, dataupdate and distribution, and other relevant information to show how display design will provide information needed for successful mission implementation.

3. **Verification Plan and Outcomes:** Provide a brief overview of the verification plan. Identify the test program approach relative to development, qualification, and acceptance testing. Define the planned temperature levels and test phases applicable to component, subsystem, and system level testing. Identify any anomalies that impact the performance of the system.

4. **Operational Analysis and Constraints:** Describe operational analysis, including: operational scenarios and modes including subsystem limitations on any aspect of vehicle flight, performance and margin analysis, operating analysis, operating **environments** (induced and natural), failure modes and redundancy operations including vehicle failure modes accommodated by subsystem and failure modes reacting to vehicle failures as part of the overall Fault Management and System Autonomy (FMSA) design and implementation. Describe inflight maintenance or initialization procedures and parameters.

5. **Issues and Non-Conformances:** Provide a summary, including description of issue, rationale for closure and risk acceptance of requirementnon-compliances, hardware non-conformances, and a list of Material Review Boards or non-conformances at the sub vendor. Identify any known issues with the current **design and, if possible, a plan for resolving those issues. Identify any requirements that are not being met and, if possible, impacts if the current design is accepted, possible design fixes, and impacts of implementing those fixes.**

6. **System Analyses: For each analysis the contractor shall deliver a standardize report format to** include: Relevant part and serial numbers (if applicable), Analysis cycle (if applicable), Objectives/Motivation for the analysis, Study Requirements and Constraints, Assumptions and ground rules, Initializing Data, Analysis tools, tests, and Models used, Modeling technique, Internal Verification and Validation of the results (if applicable), Uncertainty of the results, Description of sensitivities, Detailed results and Key findings/recommendations . Below are specific analyses or descriptions requested in the design data book, such as:

- Worksite Analysis: This further describes and illustrates the expected physical interactions between the crew and their system interfaces as identified in task analysis.

- Human Error Analysis (HEA): See DRD-
- Anthropometric Analysis: The purpose of the requirements/analysis. Thus, it is necessary that the designers and developers show by means of analysis, modeling, and physical testing, each design against the anthropometric requirements. The contractor shall provide Anthropometric Analysis as described in Section 4.5.2 Design for Anthropometry of NASA/TP-2014- 218557 Human Integration Design Processes (HIDP) and Section 4 Anthropometry, Biomechanics, and Strength of NASA/SP-2010-3407 Human Integration design Handbook (HIDH).
- The Crew Operational Loads Report is intended to provide NASA with insight into the system developers' design to ensure crew interfaces extend to the entire anticipated crew population and considers worst-case crew load scenarios. It is anticipated that this report will be fulfilled by artifacts needed by the provider in the normal course of design and development. Crew Operational Loads Analysis will evaluate tasks as identified through Task Analysis and shall include EVA and IVA loads.
- A Vibration Analysis will describe how crew exposure to environmentally induced vibration loads is limited and/or mitigated to remain within associated standards. Instances of environmentally induced vibration loads are identified as part of Task Analysis. The analysis requires the following data from the module:
    - Description of how the human is coupled to the vehicle during all phases of flight (i.e. restraints, floor)
    - NASTRAN models or equivalents to support the Vibration Analysis
    - Identification of propulsion systems and other vibration sources
    - Crew cabin layout, restraint configuration, and design
    - The Ionizing Radiation Exposure Analysis (IREA) documents the approach of the system/module design and development team to ensure compliance with the system/module-level radiation requirements. Plan must identify significant design and challenges and be updated continually to include results of current testing, analyses, and radiation exposure mitigation strategies and efforts. Early development testing is required as part of the IREA to be used in analysis for development of radiation mitigations. It provides the information necessary for subject matter experts to have adequate insight to perform appropriate. The IREA includes the schedule for completing radiation exposure assessment milestones, applicable system/module-level radiation requirements that are agreed to at the System Requirements Review (SRR), sub-allocation of the system/module-level radiation requirements to individual components, subsystems and integrated hardware, identification and rationale. Contents shall include expected crew exposure, crew risk

	and various intravehicular location exposures for nominal environmental conditions. Design reference Solar Particle Event environment for a fully integrated vehicle(s) for each operational phase as provided by NASA.

6. FORMAT
Initial Delivery is delivered electronically on Contractor Collaboration Site Final Delivery is delivered electronically its entirety on NASA Collaboration Site

F.5-1 Developmental HITL Testing

1. DESCRIPTION/USE:
Developmental Human-in-the-loop (HITL) Testing should be planned using an over-arching strategy for how HITL testing will be used during system development. HITL testing should be conducted to evaluate and improve user interface designs beginning with concept development through verification and certification. To ensure that this approach is adequate for identifying and addressing issues, a Strategic HITL Test Plan is needed early in the development cycle. In addition to the strategy, individual event test plans and test results are to be delivered for NASA insight and feedback to the system design and requirement compliance progress.
2. INITIAL SUBMISSION:
Strategic HITL Test Plan submitted for SDR
3. SUBMISSION FREQUENCY:
Event HITL Test Plans submitted prior to each test event. HITL Test Reports submitted 30-days after each test event. HITL Test Strategy updated and resubmitted prior to PDR and CDR.
4. REMARKS:
5. DATA PREPARATION INFORMATION:
a. SCOPE:
All HITL testing planned from initial concept development through verification and certification.
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
The Strategic HITL Test Plan should describe the developer's plans for using HITL testing throughout their design process. The Strategy should include a description of test articles, test events, test objectives, test measures, and schedule. HITL test measures should include task errors (number and type), usability ratings, test subject comments, cognitive workload for assessment, and anthropometric analysis for the system design in order to identify effective design features and those that need changes or improvements. HITLs should be conducted iteratively during development to measure improvement as the design matures. Additional information on evaluation methods for usability, workload, and handling qualities can be found in NASA/TP-2014-218556 Human Integration Design Processes. When performed methodically, the iterative test and design process will result in system designs that will support crew in achieving mission objectives with required accuracy (effectiveness) and timeliness (efficiency). Test plans for each HITL test event should include specific test objectives, detailed description of the test article(s), test setup, test subject selection and training, test instruments, and data collection and analysis methods.

	Test reports for each event should confirm execution to plan or describe any deviations, provide detailed results (not just “pass/fail”), and discuss forward work based on assessment of results. Developmental HITL test strategy, plans, and results should show how developmental testing with human users is being used to evaluate and iterate crew interface designs to ensure the system will accommodate the physical and cognitive characteristics and capabilities of the crew population, and enable crew to perform tasks required to achieve mission objectives with acceptable usability and error.
6.	**FORMAT**
	Electronic file that is searchable. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining”.

F.5-2 Human-In-The-Loop (HITL) Testing

1. DESCRIPTION/USE:
Human-in-the-loop (HITL) testing should be conducted to evaluate and improve user interface designs beginning with concept development through verification and certification. To ensure that this approach is adequate for identifying and addressing issues, a Strategic HITL Test Plan is needed early in the development cycle. In addition to the strategy, individual event test plans and test results are to be delivered for NASA insight and feedback to the system design and requirement compliance progress. While the Strategic and event HITL Test Plans require NASA approval, the reports only require NASA participation for feedback.
2. INITIAL SUBMISSION:
See Attachment DRD Submission Matrix
3. SUBMISSION FREQUENCY:
See Attachment DRD Submission Matrix
4. DATA PREPARATION INFORMATION:
a) SCOPE: All HITL testing planned from initial concept development through verification and certification.
b) APPLICABLE DOCUMENTS:
c) REMARKS:
d) CONTENTS
The Strategic HITL Test Plan should describe the developer's plans for using HITL testing throughout their design process. The Strategy should include a description of test articles, test events, test objectives, test measures, and schedule. HITL test measures should include task errors (number and type), usability ratings, test subject comments, cognitive workload for assessment, and anthropometric analysis for the system design in order to identify effective design features and those that need changes or improvements. HITLs should be conducted iteratively during development to measure improvement as the design matures. Additional information on evaluation methods for usability, workload, and handling qualities can be found in NASA/TP-2014-218556 Human Integration Design Processes. When performed methodically, the iterative test and design process will result in system designs that will support crew in achieving mission objectives with required accuracy (effectiveness) and timeliness (efficiency). Test plans for each HITL test event should include specific test objectives, detailed description of the test article(s), test setup, test subject selection and training, test instruments, and data collection and analysis methods. Test reports for each event should confirm execution to plan or describe any deviations, provide detailed results (not just "pass/fail"), and discuss forward work based on assessment of results. Developmental HITL test strategy, plans, and results

should show how developmental testing with human users is being used to evaluate and iterate crew interface designs to ensure the system will accommodate the physical and cognitive characteristics and capabilities of the crew population, and enable crew to perform tasks required to achieve mission objectives with acceptable usability and error.
5. FORMAT
Electronic file that is searchable. Changes to the Strategic HITL Test Plan shall be incorporated by complete reissue. Changes shall be highlighted using track changes "redlining". Test plans and reports shall be maintained on a shared repository maintained by the contractor.

F.6-1 Human Error Analysis

1. DESCRIPTION/USE:
The Human Error Analysis (HEA) DRD is a key component of human rating a NASA spacecraft. This DRD is intended to provide NASA with insight into the system developers' approach to managing human error. Human operators make an irreplaceable contribution to the resilience of space systems, however crewed space systems must be designed with the recognition that human error is a threat that must be managed. NASA's Human-Rating Requirements for Space Systems (NPR 8705.2C) calls for Program Managers to conduct a human error analysis (HEA) during system development. The analysis should cover all mission phases, including ground processing, launch preparation, flight, and recovery/disposal operations. The requirement makes it clear that HEA is a *qualitative* analysis that complements probabilistic hazard assessments. The purpose of HEA is to identify human errors that could lead to catastrophic outcomes and use this information to influence decisions related to design, operations, and testing to manage the threat. The HEA process sees human error as a symptom of system deficiencies. The HEA analyst addresses the threat of human error by identifying mitigations at a system level, including changes to the design of hardware, software, and processes. A valuable outcome of the HEA is the identification of "error traps". These are design features or other circumstances that can provoke a specific error on a specific task. Error traps can involve hardware, software, procedures, training, or other aspects of system design and operation. Error management strategies are applied according to the following precedence: a. Design the system to prevent human error in the operation and control of the system. b. Design the system to reduce the likelihood of human error and provide the capability for the human to detect and correct or recover from the error. c. Design the system to limit the negative effects of errors. Guidance on the conduct of the HEA can be found in the following documents: Guidance for Human Error Analysis (HEA) NASA Engineering Safety Center Position Paper NESC-NPP-18-01368. Human Integration Design Processes (HIDP), NASA/TP-2014-218556.
2. INITIAL SUBMISSION:
At PDR.
3. SUBMISSION FREQUENCY:
Updated at CDR and ORR.
4. REMARKS:
The HEA analysis will be part of the Human-Systems Integration Team as defined in NPR 8705.2C § 2.3.8.
5. DATA PREPARATION INFORMATION:
a. SCOPE:
The HEA will cover all mission phases, including responses to system failures and abort scenarios. The HEA will consider human errors that could result in the death or permanent disability of the occupant(s) of a crewed space system. The HEA report is an iterative document that will be expanded and updated throughout the system development process. The human error analysis includes all mission operations while the flight crew is interacting with the space system, ground control operations, and (at a minimum) ground processing operations

with flight crew interfaces. Due to the very large number of ground crew tasks, the HEA analyst must apply a systematic method to screen in the most critical ground processing tasks for examination. The screening method for ground crew tasks must be clearly described in the HEA report. While the potential critical errors of ground processing personnel are to be considered, their personal safety is outside the scope of this DRD.
b. APPLICABLE DOCUMENTS:
Human System Integration Plan Human Rating Certification Package (HRCP)
c. CONTENTS:
A HEA report will be included in the Human Rating Certification Package (HRCP) and will be updated throughout the system development process. In addition to introductory material outlining the purpose and scope of the HEA, the HEA report should comprise two major sections, as follows: Section 1: The first section of the HEA report should provide an overview of the activities outlined in the HSI plan independent of the HEA. The report will describe how these activities identified identify potential human error and the system improvements that resulted from these activities. This section will typically describe the application of human factors standards, crew workload evaluations, human-in-the-loop usability evaluations, and hazard assessments. This section may refer to other activities, such as safety analyses, and may also contain: A review of relevant information from other analyses that were made available to the HEA team (e.g., PRA). A description of how the planned HSI and analysis activities enabled identification of potential catastrophic errors. A list of system improvements made to address human error. Section 2: The second section describes the HEA approach taken to identify potentially catastrophic errors not captured by the other activities outlined in the HSI plan, and the error management mitigations that were implemented as a result of the HEA. Mitigations may include changes to the design of hardware, procedures, or training. This section will describe: The screening approach used to identify areas for analysis. The task analysis method used to identify human tasks. The analysis methods used to analyze errors. A task-based human error analysis listing for each analyzed task the identified error-producing conditions, potential catastrophic errors, and the error management mitigations as implemented or recommended.
6. FORMAT
HEA Report in searchable PDF. Task Based Human Error Analysis in electronic file exportable to csv format. For each identified potential error, task based human error analysis file will include (a) task description, (b) error-producing conditions, including error traps (if identified) (c) description of potential error (d) Error management strategy.

F.6-2 Human-Centered Task and Error Analysis

1. DESCRIPTION/USE:
Human-Centered Task and Error Analysis is a key component in human rating a NASA spacecraft. The Project Task List is a comprehensive list of all internal and external tasks that require human interaction with or within the Project. The Human Error Analysis (HEA) builds on the Project Task List, and identifies sources and types of human error, consequences of the error, the controls to mitigate the error, and verification of controls. The Task List is developed by performing a task analysis that identifies human interactions that are necessary in order to operate, monitor, or make decisions. Design constraints and parameters necessary for human-centered design are also identified and defined. The Project Task List is used to ensure that the Project's design accounts for all identified human tasks and that the Master Task List appropriately addresses all inter- and intra- Project tasks across Project X. The Human Error Analysis is used to ensure that the Project's design accounts for potential human errors and that the Human Error Analysis can address human error comprehensively across Project X. The HEA Report provides a comprehensive summary of efforts to date for identifying and mitigating human error for the Project. It shows that the contractor's human error approach and methodology is used throughout the design cycle to identify and correct for potential human error. The relevant information provided in the report is then compiled into the X HEA Report and submitted as part of the Human Rating Certification Package.
2. INITIAL SUBMISSION:
See Attachment Submission Matrix
3. SUBMISSION FREQUENCY:
See Attachment Submission Matrix
4. **REMARKS:**
5. **DATA PREPARATION INFORMATION:**
SCOPE: The Human-Centered Task and Error Analysis includes all mission operations (nominal, off-nominal, and emergency) while the crew is interacting with the space system. This includes flight crew interfaces and mission and launch control operations within the Project's responsibility. These analyses include hardware and software interactions, interaction with automated systems, maintenance tasks, response to system failures, and abort scenarios. An operator is defined as any human that commands or interfaces with the space system during the mission, including humans in the control centers.
a. APPLICABLE DOCUMENTS:
b. CONTENTS:
1. Project Task List - The Task List identifies ground and crew tasks involving interaction with controls, displays, information, hardware, software, or equipment. For each task, parameters and conditions that affect it (enabling or limiting) are defined. Ground and crew tasks may be provided in separate task lists as long as any interaction between ground and crew during a task is

identified and explained. The crew task analysis provides information for each of the fields in the attached Task Analysis Template spreadsheet. Ground tasks shall utilize as many of the fields as relevant- noting that some are specific to flight crew.

2. Human Error Analysis - The HEA analyzes the tasks defined in the Project Task List to identify sources and type of human error actions, the consequence of the error on the system including identifying whether it can lead to a catastrophic or critical hazard/event, the specific controls to mitigate the errors, and the verification method for the control. For errors leading to catastrophic events, the HEA should identify the corresponding Hazard Analyses or Reports. Since this analysis builds upon the Project Task List, it can be delivered stand alone or with the Task List as a single product. If delivered as a stand-alone product, the tasks in the HEA and the tasks in the Task List should be linked.
3. Human Error Analysis Report - The HEA Report provides a comprehensive summary of efforts to date for identifying and mitigating human error for the Project. It shows that the HEA was iteratively and effectively used to make design decisions and operation-risk trades by:
   a) Providing an overview of the methodology, processes, and organizational approach to understand and manage potential catastrophic hazards that could be caused by human errors by using the Project Task List, Human Error Analysis, Hazard Analyses, and Probabilistic Risk Assessment results.
   b) Providing examples of how the process has been used to control human error by influencing the design, application of testing, and operations .
   c) Identifying potential errors or risks that were not addressed, and rationale for not addressing the error or risk.
   d) Assessing any residual risk.

7. FORMAT:

The Task List and Human Error Analysis shall be delivered in CSV-compatible format. The Human Error Analysis Report shall be delivered in a searchable electronic format. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining.”

F.7-1 Human Systems Integration Plan

1. DESCRIPTION/USE:
The Human Systems Integration Plan (HSIP) describes the over-arching strategy and processes for how the provider will implement human centered design and human systems integration. The HSIP summarizes the planned technical and managerial approach to implementing HSI for a program/project, throughout its life cycle. The HSIP is the first step in the process of planning and executing an HSI Program, helps a PM to reduce risk, and provides the mechanism to proactively identify and resolve potential issues before they impact program success.
2. INITIAL SUBMISSION:
Preliminary due at MCR. (DRD Type 2)
3. SUBMISSION FREQUENCY:
Baseline at SRR (DRD Type 1) and update as required. (DRD Type 1)
4. **REMARKS:**
Used to support verification of all HSI requirements. DRDs associated with this DRD are: Task Analysis, Worksite Analysis, Human Error Analysis, Information Design Analysis, Developmental HITL Testing, Anthropometric Analysis, Crew Operating Loads Report, OpNom, Labeling Plan, Vibration Analysis, Acoustic Noise Control Plan, Vehicle and System Chemicals, Contamination Control Plan, and Ionizing Radiation Exposure Analysis.
5. **DATA PREPARATION INFORMATION:**
a. SCOPE:
The HSIP is project-specific plan required by NASA policy for Projects, Single-Project Programs, and Tightly-Coupled Programs. The HSIP documents the strategy for and planned implementation of HSI through a particular project's life cycle. The purpose of the HSIP is to document and plan the scope of HSI for the effort, identify the steps and metrics used throughout the project's life cycle, identify the HSI domains engaged in the effort, and document the HSI methodologies and approaches to be taken to ensure effective HSI implementation.
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
The Human Systems Integration (HSI) Plan describes the over-arching strategy and processes for how the provider will implement human centered design and human systems integration. It will show how this integration is done throughout the systems development process to ensure the human performance characteristics are integrated into the system to: identify and reduce human error; prevent the environment from injuring the crew, and enable the crew to achieve mission objectives with required accuracy (effectiveness) and timeliness (efficiency). The HSI strategy shall describe the steps that will be taken to understand how the user will fit into the mission and environment; develop, evaluate, and refine design solutions. It will describe how the participation of users, stakeholders, and discipline experts throughout the development process is achieved. It will describe HSI team member composition, roles and responsibilities, and interaction with other engineering, safety, and operations teams including NASA participation. The plan should set expectations and provide the basis for planning technical interchange meetings, reviews, and

evaluations. Processes should also be established for deliberating and resolving human system design and evaluation issues and determining design trades. This Plan should address how the HSR DRDs fit into the HSI design strategy. Additional information on human centered design and the human systems integration team can be found in NASA/TP-2014-218556 Human Integration Design Processes. Details regarding Human Systems Integration and an example plan template can be found in NASA/SP-20210010952, NASA Human Systems Integration (HSI) Handbook, Appendix A.
6. **FORMAT**
Electronic file that is searchable. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining”.

F.7-2 Human Systems Integration Plan

1. DESCRIPTION/USE:
The Human Systems Integration (HSI) Plan describes the over-arching strategy and processes for how the provider will implement human centered design and human systems integration. It will show how this integration is done throughout the systems development process to ensure the human user capabilities and limitations are integrated into the system to: identify and reduce human error; prevent the environment from injuring the crew and enable the crew to achieve mission objectives with required accuracy (effectiveness) and timeliness (efficiency).
2. INITIAL SUBMISSION:
See Attachment Submission Matrix
3. SUBMISSION FREQUENCY:
See Attachment Submission Matrix
4. **REMARKS:**
Used to support verification of all HSR requirements . DRDs associated with this are: Human-Centered Task and Error Analysis, HITL Testing, OpNom, Labeling Plan, Acoustic Noise Control Plan, Vehicle and System Chemicals, Contamination Control Plan, and the Crew Systems, Habitation, Utilization and Stowage System Data Book.
5. **DATA PREPARATION INFORMATION:**
a. SCOPE:
The HSIP includes the over-arching strategy and processes for how the provider will implement human centered design and human systems integration throughout the systems development process to ensure the human user capabilities and limitations are integrated into a system that will support crew in achieving mission objectives with required accuracy (effectiveness) and timeliness (efficiency).
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
The Human Systems Integration (HSI) Plan describes the over-arching strategy and processes for how the provider will implement human centered design and human systems integration. It will show how this integration is done throughout the systems development process to ensure the human user capabilities and limitations are integrated into the system to: identify and reduce human error; prevent the environment from injuring the crew and enable the crew to achieve mission objectives with required accuracy (effectiveness) and timeliness (efficiency). The HSI strategy shall describe the steps that will be taken to understand how the user will fit into the mission and environment; develop, evaluate, and refine design solutions. It will describe how the participation of users, stakeholders, and discipline experts throughout the development process is achieved. It will describe HSI team member composition, roles and responsibilities, and interaction with other engineering, safety, and operations teams including NASA participation. The plan should set expectations and provide the basis for planning technical interchange meetings, reviews, and evaluations. Processes should also be established for deliberating and resolving human system design and evaluation issues and determining design trades. This Plan should address how the HSR DRDs fit into the HSI design strategy.

Additional information on human centered design and the human systems integration team can be found in NASA/TP-2014-218556 Human Integration Design Processes. Details regarding Human Systems Integration and an example plan template can be found in NASA/SP-20210010952, NASA Human Systems Integration (HSI) Handbook, Appendix A.
6. **FORMAT**
Electronic file that is searchable. Changes shall be incorporated by complete reissue. Changes shall be highlighted using track changes “redlining”.

F.7-3 Human Systems Integration Plan

DATA REQUIREMENTS DESCRIPTION	
1.TITLE Human Systems Integration (HSI) Plan	**2. NUMBER** DRD-SE-01

3. USE

The HSI Plan summarizes the technical and managerial approach to implementing HSI for the X Project, throughout its life cycle. The plan describes the approach for implementing and integrating HSI processes into the project to ensure human performance and safety requirements are appropriately considered and incorporated into the system design.

4. PREPARATION INFORMATION

REFERENCE:

SUBMISSION FREQUENCY: The maturity and amount of content in the HSI Plan shall increase over the execution of the project per Table 1. The plan's evolution will be updated throughout the project's life cycle and as driven by other significant system engineering project events, such as design reviews and/or milestone decisions. HSI Plan updates will coincide with the project technical evolution and can be used to assess/resolve HSI-related issues.

TABLE 1: Submission Frequency and Maturity

	At proposal submission	At SRR	Component & Subsystem Ground Test	At PDR	At CDR	Integrated Ground Test	Pre-flight Test	At PFAR
Human Systems Integration Plan	Initial approach	Baseline		Update	Update	Update	Update	Update

ACCEPT: Project accepted via Human Systems Integration Lead, Lead Systems Engineer, Chief Engineer

DATA PREPARATION INFORMATION: Tailor HSI Plan Content Outline found in Human Systems Integration (HSI) Handbook, Appendix A

CONTENT: This HSI Plan defines the Contractor's approach and process to implement and integrate HSI principles into the overall project development, ground test, and flight test effort. The plan is project specific and may be tailored to the scope of the project but should define the approach for the integration of human performance characteristics into the system design (to include operators, maintainers, and support personnel, as applicable). Tailored to specific project needs, the HSI Plan should address:

- Contractor's project specific definition and purpose of HSI.
- Identification of HSI personnel leadership (roles and responsibilities) and/or support to working groups, management boards, etc.
- Overview of HSI-related requirements for the system.
- An approach for incorporating the human requirements into all aspects of system development, training, operation, maintenance, and support.

FORMAT: MS Word .docx file and/or Adobe PDF

(CONTINUED)

- Identification of HSI documentation to be used throughout system development as consistent with the Contractor's HSI approach, processes, and analysis.
- An approach for identification and mitigation of HSI-related risks.
- Description of entrance and success criteria as requested in the Insight Implementation Plan (DRD-PM-01) for life cycle reviews.

The HSI Plan will evolve and be updated throughout the project's life cycle and as driven by other significant system engineering project events, such as design reviews and/or milestone decisions. Plan updates will coincide with technical evolution and can be used to assess/resolve HSI related issues.

FORMAT: MS Word .docx file and/or Adobe PDF

END OF DRD-SE-01

F.8 Information Design Analysis

1. DESCRIPTION/USE:
The information design DRD is intended to use the provider's design development work to provide NASA with insight into the system developers' design for human crew interfaces. This is done by reviewing the provider's internal design standards, plans or processes related to how they convey information needed by the crew and operators. It is anticipated that this DRD will be fulfilled by artifacts needed by the provider in the normal course of design and development. The analysis should describe the logical flow and presentation of information on electronic displays that are design to support crew tasks. The analysis should include a clear description of displays including content, layout, display flow, navigation tools, display labeling and character sizes, use of color, use of icons, data update and distribution, and other relevant information to show how display design will provide information needed for successful mission implementation. An effective and efficient design supports task performance without mental transposition, computation, memory, or repetitive navigation.
2. INITIAL SUBMISSION:
Prior to PDR
3. SUBMISSION FREQUENCY:
Updates submitted prior to CDR and submitted with applicable verification test plans and closure notices (VCNs).
4. REMARKS:
5. DATA PREPARATION INFORMATION:
a. SCOPE:
Information design encompasses the presentation of information needed by human crew and operators to perform functions, as determined through task analysis, for activities such as mission planning, mission operations, system maintenance, and system health and status monitoring.
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
6. FORMAT
Electronic file that is searchable

F.9 Ionizing Radiation Exposure Analysis

1. DESCRIPTION/USE:
The Ionizing Radiation Exposure Analysis (IREA) documents the approach of the system/module design and development team to ensure compliance with the system/module-level radiation requirements. Plan must identify significant design and challenges and be updated continually to include results of current testing, analyses, and radiation exposure mitigation strategies and efforts.
2. INITIAL SUBMISSION:
Prior to PDR
3. **SUBMISSION FREQUENCY:**
Updates to the IREA must be provided at major design milestones including but not limited to the Critical Design Review (CDR) and with applicable verification test plans and closure notices (VCNs) Changes shall be incorporated by complete reissue. Changes to the analysis document shall be highlighted using track changes “redlining”.
4. **REMARKS:**
Early development testing is required as part of the IREA to be used in analysis for development of radiation mitigations. It provides the information necessary for subject matter experts to have adequate insight to perform appropriate
5. DATA PREPARATION INFORMATION:
a. SCOPE:
The IREA includes the schedule for completing radiation exposure assessment milestones, applicable system/module-level radiation requirements that are agreed to at the System Requirements Review (SRR), sub-allocation of the system/module-level radiation requirements to individual components, subsystems and integrated hardware, identification and rationale.
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
Expected crew exposure, crew risk and various intravehicular location exposures for nominal environmental conditions. Design reference Solar Particle Event environment for a fully integrated vehicle(s) for each operational phase as provided by NASA.
6. **FORMAT**
Searchable electronic file

F.10 Labeling Plan

1. **DESCRIPTION/USE:**
Crew interface labeling is needed on hardware, equipment, and habitable volumes with which crew interaction is planned, whether nominal, off-nominal, or emergency. Categories of labeling include, but are not limited to: 1. Hazard, caution and warning, emergency use 2. Location coding and orientation 3. Instructional 4. Displays and controls 5. Equipment identification 6. Inventory Management System Barcode 7. Cable and Hose Connector-end 8. IVA Labels 9. EVA Labels
2. INITIAL SUBMISSION:
Prior to PDR
3. **SUBMISSION FREQUENCY:**
Updated Labeling Plan should be delivered prior to CDR. Final Labeling Plan should be delivered with the parent requirement verification closure notice as verification evidence.
4. **REMARKS**:
5. DATA PREPARATION INFORMATION:
a. SCOPE:
Plan for labeling for crew interfaces with hardware, equipment, and habitable volumes
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
The labeling plan should include information such as, but not limited to: description of label content, dimensions, material, color(s), text size, icons and their definitions, and location or position (on hardware, equipment, or habitable volume). Refer to NASA/TP-2014-218556 HIDP section 4.13 User Interface Labeling Design for additional information on labeling plans and design. The labeling plan should show how labeling design will meet the parent Operability requirement by enabling the crew to perform tasks required to achieve mission objectives. The labeling plan should also include ensuring compliance with the OpNom Database.
6. **FORMAT**
Searchable electronic document

F.11 Task Analysis

1. DESCRIPTION/USE:	
Task analysis is a core product, anchoring and scoping much of human crew interface design. The Task Analysis DRD is intended to leverage the provider's design development work to provide NASA with insight into the system developers' design for human crew interfaces. Typically, the initial task analysis is done early in the Concept and Technology Development phase when baseline mission concepts, requirements, technologies, and the human role are being developed. To design effective and suitable systems for human use, the task analysis includes all functions of the system with which the human crew and ground operators will interact to operate, monitor, make decisions, or take actions through all mission phases. Tasks include but are not limited to operating and maintaining systems and hardware, preparing and consuming food and beverages, performing healthcare or medical procedures, recreation, and sleeping. The task analysis also serves to communicate and integrate the expected crew and operator interactions across and between systems and subsystems. Task analysis is updated as concept of operation (ConOps) and preliminary designs are developed, prototyped, tested, and evaluated. By the critical design phase, task analysis should be a mature product that is used to guide operational procedures development and the selection of task sequences and scenarios for HITL verification testing. The task analysis is a key tool for ensuring that systems and their interfaces are designed so that the human crew will be capable of operating and living with the systems to successfully accomplish the intended mission while maintaining physical and psychological health.	
2. **INITIAL SUBMISSION:**	
SDR	
3. **SUBMISSION FREQUENCY:**	
Updates submitted prior to PDR and CDR and submitted with applicable verification test plans and closure notices (VCNs). Changes shall be incorporated by complete reissue. Changes to the analysis document shall be highlighted using text redlining	
4. **REMARKS:**	
5. **DATA PREPARATION INFORMATION:**	
a. SCOPE:	
The task analysis identifies crew tasks involving interaction with controls, displays, information, hardware, or equipment. For each task, parameters and conditions that affect it (enabling or limiting) are to be defined. Tasks are typically derived from the ConOps.	
b. APPLICABLE DOCUMENTS:	

c. CONTENTS:

The analysis shall include but is not limited to the following fields for each task identified:

Title	Description
Mission Phase	Tasks should be identified by mission phase to ensure relevant task conditions are identified.
Task/Subtask Name	Name of task or subtask
System	Name of system that task interface belongs to (e.g., Avionics, Mission Control)
Subsystem	Name of subsystem that task interface belongs to (e.g., piloting control panel)
Description of Task	Include tasks performed during mission by flight crew, ground control, or automation
Task Procedure	Identify procedure document/section for given task.
Task Type	Nominal, Contingency, Emergency
Task Criticality	Identify safety criticality of task (e.g., Crit 1 (loss of life or vehicle), Crit 2 (loss of mission), or lower)
Task Prime	Identify primary responsibility for given task (e.g., flight crew, ground control, automation)
Crew Member	Identify crew member who will/can perform task (e.g., pilot, any)
Minimum Number Crew Required	Identify number of crew required to complete given task
Parallel or Serial Task	Parallel or Serial; if parallel, identify task.
Task Dependencies	Identify any other tasks that must be completed in order for the given task to begin.
Trigger to Start Task	Identify what will trigger crew to begin given task.
Trigger to End Task	Identify what will trigger crew to terminate given task performance.
Duration of Task	e.g., input only, seconds, minutes, varied
Frequency of Task	e.g., once
Time Constraint	Is task performance time-critical? If yes, what is time to effect (e.g., time constraint for buttoning up suit in cabin depressurization scenario)?
Tool Required	Identify any tool(s) required to perform task
Worksite	Location of task interface (e.g., forward stowage area)
Interface Element	Hardware and/or software interface for task performance (e.g., connector, switch, control panel, ECLSS page, etc.)

Task Type for Illumination	e.g., paper procedure or checklist reading, stowage identification, food prep, backlit display, etc.
Out-Of-View Control	Yes or No
Visual Task	Does the task require visual performance? If so, does it require reading of text?
Posture	What is the crew body posture for performing the task?
Restrained or Constrained Reach	Identify if the task includes a restrained, confined, or obstructed reach.
Critical Anthropometric Dimension & Value	Identify any critical dimensions for task or worksite, especially if restrained or constrained reach (e.g., thumb tip reach, gloved hand turn, bi-deltoid breadth etc.), from NASA anthropometry dataset.
Critical Strength Motion & Value	Identify strength motion required to perform task (e.g., single-arm cranking, finger-tip rotation, etc.). Identify crew minimum and maximum force capabilities for the strength motion, from NASA strength dataset.
Task Stability Required	Yes or No, will stability aid be needed for task performance?
Task Mobility Required	Yes or No, will mobility aids be needed for task performance (e.g., unassisted crew egress from seat through hatch)?
Gravity Environment	e.g., earth, lunar, or micro-gravity; moderate g acceleration (2 - 3 g), high g acceleration (3+ g); etc.
Vibration Environment	Yes or No
Shock Environment	Yes or No
Suit Condition	Unsuited, Suited-Unpressurized, Suited-Pressurized
Crew Demand	Expected cognitive or physical workload for given task (e.g., N/A, Minimal (simple task), Moderate (complex task requiring focused attention but crew will have spare cognitive or physical capacity during task performance); Substantial (complex task requiring dedicated attention where crew will have no extra capacity during task performance))

6. **FORMAT**

Electronic file exportable to csv format. Typically, a task analysis is done in a spreadsheet, with the tasks listed down the first columns, with the other fields in 15.3 Contents listed across the top. The filter functions of a spreadsheet make assessment much easier than in other formats.

F.12 Vehicle and System Chemicals

1. DESCRIPTION/USE:
Used to perform toxicological evaluation of system chemicals per JSC 27472
2. INITIAL SUBMISSION:
Prior to PDR
3. SUBMISSION FREQUENCY:
Iteratively at each design milestone
4. REMARKS:
5. DATA PREPARATION INFORMATION:
a. SCOPE:
Per JSC 27472 - Requirements for Submission of Data Needed for Toxicological Assessment of Chemicals to be Flown on Manned Spacecraft, data submission is required for all Programs, including, but not limited to, ISS, CCP, MPCV, and Gateway. This distribution list/mailbox has a limited, protected distribution to only authorized NASA specialists responsible for reviewing the submitted data for toxicology, biological safety, and environmental control/life support system impacts. Based upon review/conclusions from these specialists, a flight safety Hazardous Material Summary Table (HMST) will be prepared and provided back to the submitter for inclusion of this HMST within their flight safety data package. If any information within this form is considered proprietary/limited rights, then the submitter shall clearly identify or label any information as such within this form and within the transmittal email subject and body. If necessary, this file may also be password protected prior to submittal, with the password sent via separate email or via other methods (as coordinated with NASA specialists).
b. APPLICABLE DOCUMENTS:
JSC 27472
c. CONTENTS:

Each DRD shall contain the following information:

1. Flight and Contact info:
   a. Date submitted
   b. DATE HMST NEEDED (At least 2 weeks past date submitted)
   c. Name and number of experiment or hardware
   d. Acronym
   e. OpNom
   f. Hazard System record number
   g. Kit-level / Assembly-level part number and name
   h. Module (storage)
   i. Module (use)
   j. International partner concurrence?
   k. Does this experiment involve thermal heating or combustion (e.g. furnace)?
   l. Is information proprietary? If so, please read note below and provide response in the space provided.
   m. Principal Investigator name, title, and affiliation
   n. Contact person
   o. Address (building and room number)
   p. Phone
   q. Fax
   r. e-mail
   s. Targeted Mission
   t. Previous mission information
   u. Brief summary of the experiment or conditions of use including process conditions (attach additional sheets as necessary)
2. Non-biological materials to be completed for non-biological components, including all liquids, gels, particles, or gasses contained in the payload or system:
   a. Chemical / Reaction Product
   b. Experiment Subsystem
   c. Part # of Subsystem
   d. Maximum Concentration
   e. Maximum # of Samples
   f. Maximum Amount / Sample
   g. pH of Solution
   h. Particle Size or Size Range
   i. Sample Surface Area
   j. Vapor Pressure, Partial Pressure, and Volume of Gas
   k. Solubility in Water and Henry's Law Constant
   l. Thermal Stability
   m. Known Reactive Hazards
   n. Additional Information
3. Furnace Experiment Details: If investigator has obtained experimental results indicating the amount of sample vaporized, JSC Toxicology will accept those data to inform their toxicological assessment. If such results do not exist or cannot be shared, please include the requested information about the proposed experiment below so that JSC can calculate a worst-case vaporization amount.
   a. Metal Component

b. Atomic Weight (g/mol)
c. Metal in Alloy (%)
d. Sample/Metal Weight (g)
e. Vapor Pressure (mmHg)
f. Processing Temp. (C)
g. Processing Time (sec)

4. Biological Materials: The following section is to be completed for all biological materials. If recombinant DNA or RNA are to be used, please complete the last section also.
   a. Identification of Material
   b. Origin of Biological Material
   c. Maximum Concentration per Sample
   d. Pathogenicity
   e. ATCC #, Strain, and Designation
   f. Viral Presence in Cells of Human Origin
   g. Standard Biosafety Level (BSL) if known
   h. Maximum # Samples
   i. Maximum Amount Microbiological Agents per Sample and Subsystem
   j. Additional Information
5. Recombinant DNA and RNA: The following section is to be completed ONLY if recombinant DNA or RNA will be used.
6. Identification of Material
   a. Origin of Biological Material
   b. Recombinant DNA or RNA
   c. Type(s) of Vectors and Viral Replication Capacity
   d. Use of Defective DNA/RNA with Helper Virus
   e. Size of Insert/ Total Genome
   f. Nature of Inserted Sequence
   g. Inserts Codes for Known Oncogene or Toxin
   h. Integration of Inserted DNA into Host Genome
   i. Protein(s) Produced
   j. Type(s) of Host
   k. Alteration of Host Range Resulting from Research
   l. Enhancement of Agent Virulence
   m. Research Effects on Agent Transmissibility
   n. Staff Training for Safe Handling of Agent
   o. Medical Surveillance Requirements/ Recommendations
   p. Immunization Requirements/ Recommendations

6. FORMAT

Excel workbook as provided by NASA

F.13 Vibration Analysis

1. DESCRIPTION/USE:
A Vibration Analysis will describe how crew exposure to environmentally induced vibration loads is limited and/or mitigated
2. INITIAL SUBMISSION:
Prior to PDR
3. **SUBMISSION FREQUENCY:**
Updates to the analysis must be provided at major design milestones including but not limited to the Critical Design Review (CDR) and with applicable verification test plans and closure notices (VCNs).
4. **REMARKS:**
5. **DATA PREPARATION INFORMATION:**
a. SCOPE:
A Vibration Analysis will describe how crew exposure to environmentally induced vibration loads is limited and/or mitigated to remain within associated standards. Instances of environmentally induced vibration loads are identified as part of TBR Task Analysis.
b. APPLICABLE DOCUMENTS:
ISO 2631-1: 1997
c. CONTENTS:
The analysis is to include, but is not limited to, the following: 1. Description of how the human is coupled to the vehicle during all phases of flight (i.e. restraints, floor) 2. Simulation of the vibration levels at the crew interface with the vehicle 3. Analysis using acceleration weighting as described in ISO 2631-1: 1997 4. Description of measurement location for all analysis including how analysis encompasses all anthropometry ranges 5. Analysis tool validation plan 6. Crew cabin layout, restraint configuration, and design
6. **FORMAT**
Searchable electronic document.

F.14 Worksite Analysis

1. DESCRIPTION/USE:
The worksite analysis is an extension of the task analysis from the perspective of defined work areas. It is intended to leverage the provider's design development work to provide NASA with insight into the system developers' design for human crew interfaces.
2. INITIAL SUBMISSION:
Prior to PDR
3. SUBMISSION FREQUENCY:
Updates submitted after developmental HITL testing, prior to CDR, and with applicable verification test plans and closure notices (VCNs). Changes shall be incorporated by complete reissue. Changes to the analysis document shall be highlighted using text redlining or highlighting.
4. REMARKS:
5. DATA PREPARATION INFORMATION:
a. SCOPE:
Worksites include but are not limited to areas such as research workstation, hatch opening, stowage area(s), personal hygiene area(s), trash collection area, fire extinguisher and fire ports, and EVA (as applicable).
b. APPLICABLE DOCUMENTS:
c. CONTENTS:
The worksite analysis further describes and illustrates the expected physical interactions between the crew and their system interfaces as identified in task analysis. This analysis describes and illustrates the expected physical interactions between the crew and their system interfaces as identified in task analysis. The worksite analysis helps the developer to visualize and refine the design for task flows and conflicts based on physical design parameters such as, but not limited to, position and location of interface elements with respect to the user position, posture, and anthropometry. For each worksite, describe the identified tasks crew will perform and their relevant physical characteristics such as interface element, tool required, illumination, viewing distance, crew body posture, critical anthropometric dimension and value, critical strength motion and value, stability or mobility aid location, suited condition, etc. For example, when opening a hatch, what is the crew actuated mechanism? What is the expected crew strength motion? What is the crew body posture and how will crew react forces and stabilize themselves? Will crew be wearing a suit while performing tasks? Will suit be pressurized? What are mobility or strength constraints related to suited task performance? Interactions such as these are to be defined in worksite analysis and used as a tool for communicating design concepts and design driving parameters and conditions with system teams. Design change recommendations that result from

developmental testing, analyses, and evaluations should be captured in updated worksite analyses.
6. FORMAT
Searchable electronic document (.doc, .docx or .pdf).

Appendix G. HSI Resources

The following is a list of HSI policy, guidance and scholarly publications used within the HSI community across the federal government.

G.1 NASA HSI Guidance and Documents

NASA-STD-3001, NASA Spaceflight Human- System Standard Volume 2: Human Factors, Habitability, and Environmental Health (2019)

NASA-STD-8729.1A, NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems

NPD 1000.0, NASA Governance and Strategic Management Handbook

NPR 8705.2, Human-Rating Requirements for Space Systems

NPR 8705.4A, Risk Classification for NASA Payloads

NPR 7123.1, NASA Systems Engineering Processes and Requirements

NPR 7120.5, NASA Space Flight Program and Project Management Requirements w/Changes 1-13

NPR 7120.11, NASA Health and Medical Technical Authority (HMTA) Implementation

NPR 8900.1A, NASA Health and Medical Requirements for Human Space Exploration

Engineering, Life Sciences, and Health/Medicine Synergy in Aerospace Human Systems Integration: The Rosetta Stone Project, NASA SP-2017-633

NASA/SP-2014-3705. NASA Space Flight Program and Project Management Handbook.

NASA. (2015). Cost Estimating Handbook. Version 4.0. National Aeronautics and Space Administration. Retrieved from: https://www.nasa.gov/offices/ocfo/nasa-cost-estimating-handbook-ceh

NASA Human Integration Design Processes, NASA/TP-2014-218556

NASA Human Integration Design Handbook, NASA/SP-2010-3407-Rev 1

NASA Systems Engineering Handbook (SP-2016-6105) Rev 2

NASA Systems Engineering Expanded Guidance (SP-2016-6105 - SUPPL), Volume 2

G.2 Department of Defense HSI Principles, Guidance & Policies

Army Regulation (AR) 602-2: Human Systems Integration in the System Acquisition Process (2015)

Army Pamphlet (AP) 602-2, Guide for Human Systems Integration in the Acquisition Process (2018)

Defense Acquisition Guidebook (DAG) (2018)

Defense Acquisition University HSI Community of Practice (https://www.dau.edu/cop/hsi)

DI-HFAC-80742, Data Item Description: Human Engineering Simulation Concept (2018)

DI-HFAC-80744, Human Engineering Test Report (2017)

DI-HFAC-80745, Data Item Description: Human Engineering Systems Analysis Report (2015)

DI-HFAC-80746, Data Item Description: Human Engineering Design Approach Document - Operator (HEDAD-O) (2012; Notice 1, 2017)

DI-HFAC-80747, Data Item Description: Human Engineering Design Approach Document - Maintainer (HEDAD-M) (2016)

DI-HFAC-81399B, Data Item Description: Critical Task Analysis Report (2013)

DI-HFAC-81742, Data Item Description: Human Engineering Program Plan (HEPP) (2016)

DI-HFAC-81743A Data Item Description: HSI Program Plan (HSIPP, 2020)

DI-HFAC-81833A Data Item Description: HSI Report (2019)

DoD Directive (DoDD) 5000.01, The Defense Acquisition System (2020)

DoD Instruction (DoDI) 5000.02T, Operation of the Defense Acquisition System (2020)

DoD Instruction (DoDI) 5000.02, Operation of the Adaptive Acquisition Framework (2020).

DoD Instruction 5000.PR, Human Systems Integration (HSI) in Defense Acquisition (expected 2021).

MIL-HDBK-1908, Definitions of Human Factors Terms (1999)

MIL-HDBK 29612 DoD Handbook Instructional Systems Development/Systems Approach to Training and Education (Parts 1-5, 2020/2021)

MIL-HDBK-46855A, Department of Defense Standard Practice: Human Engineering Requirements for Military Systems, Equipment, and Facilities (2011)

MIL-STD 1472, Human Engineering Design Criteria for Military Systems, Equipment, and Facilities (2020)

MIL-STD-3034, Reliability-Centered Maintenance (RCM) (2014)

MIL-STD-1474, Department of Defense Design Criteria Standard: Noise Limits (2020)

MIL-STD-882 Department of Defense Standard Practice System Safety (SSPS) (2012)

NAVSEAINST 3900.8A Human Systems Integration (HSI) Policy in Acquisition and Modernization (2005)

NAVSEASYSCOM T9640-AC-DSP-010/HAB, Rev.1, Shipboard Habitability Design Criteria and Practices Manual (Surface Ships) for New Ship Designs and Modernization (2016)

USN, OPNAV Instruction (OPNAVINST) 9640.1C, Shipboard Habitability Program (2019)

USN, OPNAV Instruction 1500.76, Naval Training Systems Requirements, Acquisition, and Management (2021)

United States Air Force Human Systems Integration Handbook (2009)

USAF Human Systems Integration Requirements Pocket Guide (2009)

G.3 Other Government Agency Guidance and Documents

Federal Aviation Administration (FAA) Human Factors Design Standards (HFDS) HF-STD-001B (2016)

FAA System Safety Handbook (2000)

NUREG 0711 (Rev 3) – Nuclear Regulatory Commission, Human Factors Engineering Program Review Model (2012)

NUREG 0700 (Rev 3)– Human System Interface Design Review Guidelines (2020)

G.4 Professional Organization Guidance and Documents

IEEE 15288.1, IEEE Standard for Application of Systems Engineering on Defense Programs (2014)

INCOSE Systems Engineering Handbook: A Guide for System Life-Cycle Processes and Activities, 4th Edition. (2015)

ISO/IEC/IEEE 15288, Systems and Software Engineering—System Life-Cycle Processes (2021)

ISO 9241-210:2019 Ergonomics of Human-System Interaction-Part 210: Human-Centered Design for Interactive Systems. (2019)

Society of Automotive Engineers (SAE) Systems Management Standard: SAE 6906 Standard Practice for Human Systems Integration (2019)

SAE JA1012, A Guide to the Reliability-Centered Maintenance Standard (2011)

G.5 Non-Government Resources

APA Handbook of Human Systems Integration (Boehm-Davis, Durso, and Lee (Eds.), 2015)

Handbook of Human-Systems Integration (Booher,H. (Ed.), 2003).

Shaver, E.R., and Braun, C.C., (2008) The Return on Investment (ROI) for Human Factors and Ergonomics Initiatives, Benchmark Research & Safety, Inc. www.benchmarkrs.com

Ergonomic Design for People at Work, Eastman Kodak Company (2003)

Handbook of Human Factors, Gavriel Salvendy (2012)

Handbook of Training Evaluation and Measurement Methods, 4th Edition, Jack J. Philips, Ph.D (2016)

Human Performance, Workload, and Situational Awareness Measures Handbook, 1st Edition, Valerie J. Gawron (2000)

Mosby's Handbook of Physiology and Anatomy, 2nd Edition, Kevin T. Patton and Gary A. Thibodeau (2014)

System Safety for the 21st Century, Richard A. Stephans (2004)

Handbook of Human Factors and Ergonomic Methods. CRC Press, Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hedreick, H. (Eds) (2006)

The Human View Handbook for MODAF. System Engineering & Assessment Ltd. Second Issue. (2009)

Appendix H. Acronyms

AFHSI	Air Force Human Systems Integration
AFRC	Armstrong Flight Research Center
AIT	Automatic Identification Technology
ALARP	As Low as Reasonably Practicable
AoA	Analysis of Alternatives
ARMD	Aeronautics Research Mission Directorate
ATF	Advanced Tactical Fighter
AU	Avionics Unit
CBM	Condition Based Maintenance
CCP	Commercial Crew Program
CDR	Critical Design Review
CERR	Critical Events Readiness Review
CHMO	Chief Health and Medical Officer
CMOs	Chief Medical Officers
ConOps	Concept of Operations
CoP	Community of Practice
COTS	Commercial Off-the-Shelf
CxP	Constellation Program
DoD	Department of Defense
DR	Decommissioning Review
DRD	Data Requirements Description
DRM	Design Reference Mission
DRR	Disposal Readiness Review
DTIC	Defense Technical Information Center
EEGS	Emergency Egress Guidance System
EELS	Emergency Egress Lighting System
ETA	Engineering Technical Authority
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FMEA	Failure Modes & Effects Analysis
FMECA	Failure Modes Effects & Criticality Analysis
FRR	Flight Readiness Review
FTA	Fault Tree Analysis
GSE	Ground Support Equipment
HAZOP	Hazard and Operability Analysis
HCD	Human-Centered Design
HEOMD	Human Exploration and Operations Mission Directorate
HFE	Human Factors Engineering
HFES	Human Factors and Ergonomics Society
HFTF	Human Factors Task Force
HH&P	Human Health and Performance
HIDH	Human Integration Design Handbook
HIDP	Human Integration Design Processes
HITL	Human-in-the-Loop
HMTA	Health and Medical Technical Authority
HRA	Human Reliability Analysis
HRA	Human Reliability Assessment
HRL	Human Readiness Level
HSF	Human Space Flight
HSI	Human Systems Integration
HSIG	Human Systems Integration Group
HSIP	HSI Plan
HSIPG	HSI Practitioner's Guide
HSIR	Human System Integration Requirements
IETM	Integrated Electronic Technical Manual (i.e., digitized data)
IMPRINT	Improved Performance Research Integration Tool
IPD	Integrated Product Development
IPT	Integrated Product Team
ISS	International Space Station
IUID	Item-Unique Identification
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JSSG	Joint Service Specification Guides
KDP	Key Decision Point
KPP	Key Performance Parameter
KSA	Knowledge, Skills, and Abilities
KSA	Knowledge, Skills, and Attitudes (training specific)
LaRC	Langley Research Center
LCC	Life-Cycle Cost
LHIC	Lead HMTA Integration Centers

LMSS	Lockheed Martin Space Systems
LOC	Loss of Crew
LOM	Loss of Mission
LORA	Level of Repair Analysis
LRU	Line Replaceable Unit
MCR	Mission Concept Review
MDR	Mission Definition Review
MOE	Measure of Effectiveness
MOP	Measure of Performance
MPT	Manpower, Personnel, and Training
MSFC	Marshall Space Flight Center
MTA	Maintenance Task Analysis
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NFS	NASA FAR Supplement
NPR	NASA Procedural Requirements
NTSB	National Transportation Safety Board
O&S	Operations and Support
OCE	Office of the Chief Engineer
OCHMO	Office of the Chief Health and Medical Officer
ORR	Operational Readiness Review
ORU	Orbital Replacement Unit
OSMA	Office of Safety and Mission Assurance
PDR	Preliminary Design Review
PFAR	Post-Flight Assessment Review
PIE	Product Integrity Engineer
PLAR	Post-Launch Assessment Review
PM	Project Manager
PMA	Portable Maintenance Aid
PRA	Probabilistic Risk Analysis
PRR	Production Readiness Review
PWS	Performance Work Statement
R&M	Reliability & Maintainability
RCM	Reliability Centered Maintenance
RDT	Requirements Development Team
RM&S	Reliability, Maintainability & Sustainability
ROI	Return on Investment
S&MA	Safety and Mission Assurance
SAGAT	Situation Awareness Global Assessment Technique
SAR	System Acceptance Review
SDR	System Design Review
SE	Systems Engineer/Engineering
SEB	Source Evaluation Board
SE&I	Systems Engineering and Integration
SEHB	Systems Engineering Handbook
SEMP	Systems Engineering Management Plan
SI	System Integration
SIM	Serialized Item Management
SIR	System Integration Review
SMA	Safety and Mission Assurance
SME	Subject Matter Expert
SRC	Sample Return Capsule
SRR	System Requirements Review
SS2	SpaceShipTwo
SSME	Space Shuttle Main Engine
STS	Space Transportation System
TA	Technical Authority
T&E	Test and Evaluation
TLI	Technical Leading Indicator
TLX	Task Load Index
TPM	Technical Performance Margin
TPM	Technical Performance Measure
TRL	Technology Readiness Level
TRR	Test Readiness Review
V&V	Verification and Validation
WBS	Work Breakdown Structure

Appendix I. Glossary

Acceptable Risk. The risk that is understood and agreed to by the program/project, governing authority, mission directorate, and other customer(s) such that no further specific mitigating action is required.

Acquisition Plan. The integrated acquisition strategy that enables a program or project to meet its mission objectives and provides the best value to NASA.

Acquisition. The process for obtaining the systems, research, services, construction, and supplies that NASA needs to fulfill its missions. Acquisition, which may include procurement (contracting for products and services), begins with an idea or proposal that aligns with the NASA Strategic Plan and fulfills an identified need and ends with the completion of the program or project or the final disposition of the product or service.

Analysis of Alternatives. A formal analysis method that compares alternative approaches by estimating their ability to satisfy mission requirements through an effectiveness analysis and by estimating their LCCs through cost analysis. The results of these two analyses are used together to produce a cost-effectiveness comparison that allows decision makers to assess the relative value or potential programmatic returns of the alternatives. An analysis of alternatives broadly examines multiple elements of program/project alternatives (including technical performance, risk, LCC, and programmatic aspects).

Approval (for implementation). Acknowledgment by the Decision Authority that the program/project has met stakeholder expectations and Formulation requirements and is ready to proceed to Implementation. By approving a program/project, the Decision Authority commits the budget resources necessary to continue into Implementation. Approval (for implementation) is documented.

Baseline (document context). Implies the expectation of a finished product, though updates may be needed as circumstances warrant. All approvals required by Center policies and procedures have been obtained.

Baseline (general context). An agreed-to set of requirements, cost, schedule, designs, documents, etc., that will have changes controlled through a formal approval and monitoring process.

Concept of Operations (ConOps) (concept documentation)**.** Developed early in Pre-Phase A, the ConOps describes the overall high-level concept of how the system will be used to meet stakeholder expectations, usually in a time-sequenced manner. It describes the system from an operational perspective and helps facilitate an understanding of the system goals. It stimulates the development of the requirements and architecture related to the user elements of the system. It serves as the basis for subsequent definition documents and provides the foundation for the long-range operational planning activities.

Configuration Management. A management discipline applied over a product's life cycle to provide visibility into and control changes to performance, functionality, and physical characteristics.

Contract. A mutually binding legal relationship obligating the seller to furnish the supplies or services (including construction) and the buyer to pay for them. It includes all types of commitments that obligate the Government to an expenditure of appropriated funds and that, except as otherwise authorized, are in writing. In addition to bilateral instruments, contracts include (but are not limited to) awards and notices of awards; job orders or task letters issued under basic ordering agreements; letter contracts; orders, such as purchase orders, under which the contract becomes effective by written acceptance or performance; and bilateral contract modifications. Contracts do not include grants and cooperative agreements.

Contractor HSI Lead. Contractor person responsible for planning, coordinating, and executing the HSI efforts; serves as the contractor's HSI single point-of-contact.

Contractor HSI Team. Refers to the contractor (typically a prime contractor) HSI team responsible for performing HSI activities under a systems acquisition contract. An "extended" HSI team may also include associate contractor, subcontractor, and supplier HSI personnel.

Contractor. This term refers to the company or organization responsible for fulfilling the system acquisition contract requirements. An alternative could be "solution provider."

Critical Design Review (CDR). A review that demonstrates that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and test, and that the technical effort is on track to complete the system development meeting performance requirements within the identified cost and schedule constraints.

Critical Event (or key event). An event in the operations phase of the mission that is time-sensitive and is required to be accomplished successfully in order to achieve mission success. These events should be considered early in the life cycle as drivers for system design.

Decision Authority (program and project context). The individual authorized by the Agency to make important decisions on programs and projects under their authority.

Decommissioning. The process of ending an operating mission and the attendant project as a result of a planned end of the mission or project termination. Decommissioning includes final delivery of any remaining project deliverables, disposal of the spacecraft and all its various supporting systems, closeout of contracts and financial obligations, and archiving of project/mission operational and scientific data and artifacts. Decommissioning does not mean that scientific data analysis ceases, only that the project will no longer provide the resources for continued research and analysis.

Derived Requirements. Requirements arising from constraints, consideration of issues implied but not explicitly stated in the high-level direction provided by NASA Headquarters and Center institutional requirements, factors introduced by the selected architecture, and the design. These requirements are finalized through requirements analysis as part of the overall systems engineering process and become part of the program/project requirements baseline. Derived non-technical requirements are established by, and are the responsibility of, the Programmatic Authority. Derived technical requirements are the responsibility of the Institutional Authority.

Design Documentation. A document or series of documents that captures and communicates to others the specific technical aspects of a design. It may include images, tabular data, graphs, and other descriptive material.

Development Costs. The total of all costs from the period beginning with the approval to proceed to Implementation at the beginning of Phase C through operational readiness at the end of Phase D.

Disposal. The process of eliminating a project's assets, including the spacecraft and ground systems. Disposal includes the reorbiting, deorbiting, and/or passivation (i.e., the process of removing stored energy from a space structure at the end of mission that could result in an explosion or deflagration of the space structure) of a spacecraft.

Domain-Specific System Requirements. System specification/technical requirements impacting the humans (operator, maintainer, supporter, or other type of user) associated with the system, to the extent that human performance, mission effectiveness, and the HSI domain design/implementation considerations may be affected. Specific HSI domains are responsible for the development, configuration management, and verification of these system-based requirements.

Engineering Requirements. Requirements defined to achieve programmatic requirements and relating to the application of engineering principles, applied science, or industrial techniques.

Environmental Impact. The direct, indirect, or cumulative beneficial or adverse effect of an action on the environment.

Flight Readiness Review (FRR). A review that examines tests, demonstrations, analyses, and audits that determine the system’s readiness for a safe and successful flight/launch and for subsequent flight operations. It also ensures that all flight and ground hardware, software, personnel, and procedures are operationally ready.

Formulation Agreement. The Formulation Agreement is prepared by the project to establish the technical and acquisition work that needs to be conducted during Formulation and defines the schedule and funding requirements during Phase A and Phase B for that work.

Formulation. The identification of how the program or project supports the Agency's strategic goals; the assessment of feasibility, technology, and concepts; risk assessment, team building, development of operations concepts, and acquisition strategies; establishment of high-level requirements and success criteria; the preparation of plans, budgets, and schedules essential to the success of a program or project; and the establishment of control systems to ensure performance to those plans and alignment with current Agency strategies.

Funding (budget authority). The authority provided by law to incur financial obligations that will result in expenditures. There are four basic forms of budget authority, but only two are applicable to NASA: appropriations and spending authority from offsetting collections (reimbursables and working capital funds). Budget authority is provided or delegated to programs and projects through the Agency's funds distribution process.

GIDEP. This acronym stands for "Government-Industry Data Exchange Program." GIDEP is a cooperative information-sharing program between the U.S. Government, Canadian Government, and industry participants. The goal of GIDEP is to ensure that only reliable and conforming parts, materials, and software are in use on all Government programs and operations. GIDEP members share technical information essential to the research, design, development, production, and operational phases of the life cycle of systems, facilities, and equipment.

Habitability and Environment. Ensuring system integration with the human through design and continual evaluation of internal/external living and working environments necessary to sustain safety, human/mission performance, and human health.

HSI Activities. The management and technical disciplines of planning, leading, coordinating, and optimizing all human integration considerations during system design, development, test, production, use, and disposal of systems, subsystems, equipment, and facilities.

HSI Issues. Issues are risks that have a likelihood of 100%, or, in other words, have been realized. HSI issues are issues that affect more than one domain.

HSI Lead. The HSI Lead is the person identified to lead the HSI effort. The lead programmatically reports to program management or SE leads as defined by the PM.

HSI Metrics. Quantitative and/or qualitative measures used to estimate the positive impact of HSI and/or HSI domains on design. Alternatively, quantitative or qualitative measures used to impact adverse consequences on the ability of HSI or HSI domains to achieve human integration, human performance, or cost reduction goals.

HSI Plan. The HSIP is project-specific plan required by NASA policy for Projects, Single-Project Programs, and Tightly-Coupled Programs. The HSIP documents the strategy for and planned implementation of HSI through a particular project’s life cycle. The purpose of the HSIP is to document and plan the scope of HSI for the effort, identify the steps and metrics used throughout the project’s life cycle, identify the HSI domains engaged in the effort, and document the HSI methodologies and approaches to be taken to ensure effective HSI implementation.

HSI Practitioner(s). Personnel trained and/or experienced in HSI or the HSI domains who participate in the execution of the HSI program. May also be called **HSI Subject-Matter Experts** (SMEs).

HSI Program. All the planning, analysis, design support, test and evaluation, coordination, and documentation activities undertaken in response to HSI programmatic requirements contained in the system acquisition contract statement of work.

HSI Programmatic Requirements. Statement of Work requirements for Human Systems Integration tasks for the contractor HSI team to execute. Focus of these requirements is on HSI program planning, coordination, execution, documentation, and reporting.

HSI Risk. A condition of potentially adverse impact on humans and/or systems. HSI risks can be technical, as well as programmatic. An example of a major HSI risk would be that the assigned personnel, trained in accordance with the training developed, will not be able to safely and effectively operate (or maintain) the system as delivered.

HSI Task. Any task performed by the HSI team or HSI domain specialist that contributes materially to achieving HSI goals of improving human integration, improving human performance, or reducing personnel-driven ownership costs.

HSI Working Group. Typically, a chartered organization charged with carrying out all the HSI activities associated with a system acquisition program. The HSI working group (which may be called an Integrated Product Team (IPT), depending on the program or service) is typically co-chaired by government and prime contractor HSI leads. Membership usually includes HSI and HSI domain representatives from the prime contractor and government. The HSI working group may also include HSI and domain representation from major subcontractors, associate contractors, and major suppliers.

HSI-Related Requirement. A requirement not directly associated with an HSI domain, but with human implications, including capability, system or lower-level specification, logistical, or human performance requirements. These requirements may interface with multiple domains and multiple disciplines. HSI or the HSI domains do not have formal responsibility for developing, managing, and testing these requirements, but are a significant stakeholder in the fulfilment of these requirements during system design/development and throughout the system life cycle.

Human Factors Engineering (HFE). Designing and evaluating system interfaces and operations for human well-being and optimized safety, performance and operability, while considering human performance characteristics as they affect and are affected by environments and operating in expected and unpredicted conditions.

Human Performance Requirements. A requirement articulating a need for attaining a specified level of human action within a particular environment, with or without system facilitation, in order to support mission attainment.

Human Performance. A measure of human functions and action in a specified environment, reflecting the ability of actual users and maintainers to meet the system's performance standards, including reliability and maintainability, under the conditions in which the system will be employed.

Human Systems Integration (HSI). A required interdisciplinary integration of the human as an element of the system to ensure that the human and software/hardware components cooperate, coordinate and communicate effectively to perform a specific function or mission successfully. HSI embraces the concept of the human as a sub-system on par with the hardware and software sub-systems, and responsible for assurance of mission success.

Human-Centered Design. An approach to the development of interactive systems that focuses on making systems usable by ensuring that the needs and performance characteristics of the human are met throughout the system's life cycle.

Human-in-the-loop (HITL). Human-in-the-loop (HITL) studies are part of an iterative process conducted for the purposes of evaluation or research. HITL studies involve realistic task scenarios, operational or analog participants, and system fidelity that increases over time. HITLs are used to reveal HSI problems; demonstrate that the operational concept meets system requirements for effectiveness, efficiency, acceptability, and safety; and/or create generalizable knowledge about humans and their interactions with and within the other elements of the system.

Implementation. The execution of approved plans for the development and operation of the program/project, and the use of control systems to ensure performance to approved plans and continued alignment with the Agency's goals.

Institutional Authority. Institutional Authority encompasses all those organizations and authorities not in the Programmatic Authority. This includes Engineering, Safety and Mission Assurance, and Health and Medical organizations; Mission Support organizations; and Center Directors.

Integration Plan. The integration and verification strategies for a project interface with the system design and decomposition into the lower-level elements. The integration plan is structured to bring the elements together to assemble each subsystem and to bring all of the subsystems together to assemble the system/product. The primary purposes of the integration plan are: (1) to describe this coordinated integration effort that supports the implementation strategy, (2) to describe for the participants what needs to be done in each integration step, and (3) to identify the required resources and when and where they will be needed.

Interface Control Document. An agreement between two or more parties on how interrelated systems will interface with each other. It documents interfaces between things like electrical connectors (what type, how many pins, what signals will be on each of the pins, etc.); fluid connectors (type of connector or of fluid being passed, flow rates of the fluid, etc.); mechanical (types of fasteners, bolt patterns, etc.); and any other interfaces that might be involved.

Key Decision Point. The event at which the Decision Authority determines the readiness of a program/project to progress to the next phase of the life cycle (or to the next KDP).

Key Performance Parameter (KPP). Those capabilities or characteristics (typically engineering-based or related to health and safety or operational performance) considered most essential for successful mission accomplishment. They characterize the major drivers of operational performance, supportability, and interoperability.

Lesson Learned. Captured knowledge or understanding gained through experience which, if shared, would benefit the work of others. Unlike a best practice, lessons learned describes a specific event that occurred and provides recommendations for obtaining a repeat of success or for avoiding reoccurrence of an adverse work practice or experience.

Life-Cycle Cost (LCC). The total of the direct, indirect, recurring, nonrecurring, and other related expenses both incurred and estimated to be incurred in the design, development, verification, production, deployment, prime mission operation, maintenance, support, and disposal of a project, including closeout, but not extended operations. The LCC of a project or system can also be defined as the total cost of ownership over the project or system's planned life cycle from Formulation (excluding Pre-Phase A) through Implementation (excluding extended operations). The LCC includes the cost of the launch vehicle.

Life-Cycle Review. A review of a program or project designed to provide a periodic assessment of the technical and programmatic status and health of a program or project at a key point in the life cycle, e.g., Preliminary Design Review (PDR) or Critical Design Review (CDR). Certain life-cycle reviews provide the basis for the Decision Authority to approve or disapprove the transition of a program/project at a KDP to the next life-cycle phase.

Maintainability and Supportability. Designing for full life cycle and simplified maintenance and accessibility, reliability, optimized resources, spares, consumables and logistics given mission constraints.

Maintainability. The measure of the ability of an item to be retained in or restored to specified conditions when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance.

Measures of Effectiveness (MOE). A measure by which a stakeholder's expectations are judged in assessing satisfaction with products or systems produced and delivered in accordance with the associated technical effort. The MOE is deemed to be critical to not only the acceptability of the product by the stakeholder but also critical to operational/mission usage. A MOE is typically qualitative in nature or not able to be used directly as a design-to requirement.

Measures of Performance (MOP). A quantitative measure that, when met by the design solution, helps ensure that a MOE for a product or system will be satisfied. These MOPs are given special attention during design to ensure that the MOEs to which they are associated are met. There are generally two or more measures of performance for each MOE.

Metric. A measurement taken over a period of time that communicates vital information about the status or performance of a system, process, or activity.

Mission Concept Review. A review that affirms the mission/project need and examines the proposed mission's objectives and the ability of the concept to fulfill those objectives.

Mission Definition Review. A life-cycle review that evaluates whether the proposed mission/system architecture is responsive to the program mission/system functional and performance requirements and requirements have been allocated to all functional elements of the mission/system.

Mission. A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution.

Operational Readiness Review. A review that examines the actual system characteristics and the procedures used in the system or product's operation and ensures that all system and support (flight and ground) hardware, software, personnel, procedures, and user documentation accurately reflects the deployed state of the system and are operationally ready.

Operations Concept (formerly Mission Operations Concept). A description of how the flight system and the ground system are used together to ensure that the concept of operation is reasonable. This might include how mission data of interest, such as engineering or scientific data, are captured, returned to Earth, processed, made available to users, and archived for future reference. The Operations Concept should describe how the flight system and ground system work together across mission phases for launch, cruise, critical activities, science observations, and end of mission to achieve the mission.

Operations. Full life-cycle engagement of operational considerations into the design, development, maintenance and evolution of systems and organizational capability to enable robust, cost-effective mission operations for human effectiveness and mission success.

Orbital Debris. Any object placed in space by humans that remains in orbit and no longer serves any useful function. Objects range from spacecraft to spent launch vehicle stages to components and also include materials, trash, refuse, fragments, and other objects that are overtly or inadvertently cast off or generated.

Preliminary (document context). Implies that the product has received initial review in accordance with

Center best practices. The content is considered correct, though some TBDs may remain. All approvals required by Center policies and procedures have been obtained. Major changes are expected.

Preliminary Design Review (PDR). A review that demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. It will show that the correct design option has been selected, interfaces have been identified, and verification methods have been described.

Program (Project) Team. All participants in program (project) formulation and implementation. This includes all direct reports and others that support meeting program (project) responsibilities.

Program Requirements. The set of requirements imposed on the program office, which are typically found in the program plan plus derived requirements that the program imposes on itself.

Program. A strategic investment by a Mission Directorate or Mission Support Office that has a defined architecture and/or technical approach, requirements, funding level, and management structure that initiates and directs one or more projects. A program implements a strategic direction that the Agency has identified as needed to accomplish Agency goals and objectives.

Programmatic Authority. Includes the Mission Directorates and their respective program and project managers. Individuals in these organizations are the official voices for their respective areas. Programmatic Authority sets, oversees, and ensures conformance to applicable programmatic requirements.

Project Plan. The document that establishes the project's baseline for Implementation, signed by the responsible program manager, Center Director, project manager, and the MDAA, if required.

Project. A spaceflight project is a specific investment identified in a Program Plan having defined requirements, a LCC, a beginning, and an end. A project also has a management structure and may have interfaces to other projects, agencies, and international partners. A project yields new or revised products that directly address NASA's strategic goals.

Risk Assessment. An evaluation of a risk item that determines: (1) what can go wrong, (2) how likely is it to occur, (3) what the consequences are, (4) what uncertainties are associated with the likelihood and consequences, and (5) what the mitigation plans are.

Risk Management. Risk management includes risk-informed decision making (RIDM) and continuous risk management (CRM) in an integrated framework. RIDM informs systems engineering decisions through better use of risk and uncertainty information in selecting alternatives and establishing baseline requirements. CRM manages risks over the course of the development and the Implementation Phase of the life cycle to ensure that safety, technical, cost, and schedule requirements are met. This is done to foster proactive risk management, to better inform decision making through better use of risk information, and then to more effectively manage Implementation risks by focusing the CRM process on the baseline performance requirements emerging from the RIDM process. (See NPR 8000.4, Agency Risk Management Procedural Requirements.) These processes are applied at a level of rigor commensurate with the complexity, cost, and criticality of the program.

Risk. In the context of mission execution, risk is the potential for performance shortfalls, which may be realized in the future, with respect to achieving explicitly established and stated performance requirements. The performance shortfalls may be related to any one or more of the following mission execution domains: (1) safety, (2) technical, (3) cost, and (4) schedule. (See NPR 8000.4, Agency Risk Management Procedural Requirements.)

Risk-Informed Decision Making. A risk-informed decision-making process uses a diverse set of performance measures (some of which are model-based risk metrics) along with other considerations within a deliberative process to inform decision making.

Safety. Implementation of safety considerations across the full life cycle to reduce hazards and risks to personnel, system, facilities and mission.

Single-Project Programs. These programs tend to have long development and/or operational lifetimes, represent a large investment of Agency resources, and have contributions from multiple organizations/agencies. These programs frequently combine program and project management approaches, which they document through tailoring.

Stakeholder. An individual or organizational customer having an interest (or stake) in the outcome or deliverable of a program or project.

Standard Practice (also Best Practice). The recommended process to be followed in implementing and executing work for a program (i.e., HSI efforts for a program) against which other practices are measured. For HSI, best practices are determined by a broad-based group of DoD and contractor SMEs, who are experienced in the practice and application of HSI on a variety of acquisition programs.

Standards. Formal documents that establish a norm, requirement, or basis for comparison, a reference point to measure or evaluate against. A technical standard, for example, establishes uniform engineering or technical criteria, methods, processes, and practices. (Refer to NPR 7120.10, Technical Standards for NASA Programs and Projects.)

Success Criteria. That portion of the top-level requirements that defines what is to be achieved to successfully satisfy NASA Strategic Plan objectives addressed by the program or project.

Supportability. Supportability is the capability of a total system design to support operations and readiness needs throughout the life-cycle of a system at an affordable cost. It provides a means of assessing the suitability of a total system design for a set of operational needs within the intended operations and support environment (including cost, equipment readiness, and manpower and personnel constraints).

System Requirements Review (SRR). For a program, the SRR is used to ensure that its functional and performance requirements are properly formulated and correlated with the Agency and mission directorate strategic objectives. For a system/project, the SRR evaluates whether the functional and performance requirements defined for the system are responsive to the program's requirements and ensures that the preliminary project plan and requirements will satisfy the mission.

System. The combination of elements that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, data, and procedures needed for this purpose. Also, the end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make up a system.

Systems Engineering Management Plan (SEMP). The SEMP identifies the roles and responsibility interfaces of the technical effort and specifies how those interfaces will be managed. The SEMP is the vehicle that documents and communicates the technical approach, including the application of the common technical processes; resources to be used; and the key technical tasks, activities, and events along with their metrics and success criteria.

Systems Engineering. A disciplined approach for the definition, implementation, integration, and operation of a system (product or service). The emphasis is on achieving stakeholder functional, physical, and operational performance requirements in the intended use environments over planned life within cost and schedule constraints. Systems engineering includes the engineering processes and technical management processes that consider the interface relationships across all elements of the system, other systems, or as a part of a larger system.

Tailoring. The process used to adjust or seek relief from a prescribed requirement to accommodate the needs of a specific task or activity (e.g., program or project). The tailoring process results in the generation of deviations and waivers depending on the timing of the request.

Technical Authority. Part of NASA's system of checks and balances that provides independent oversight of programs and projects in support of safety and mission success through the selection of individuals at delegated levels of authority. These individuals are the Technical Authorities. Technical Authority delegations are formal and traceable to the Administrator. Individuals with Technical Authority are funded independently of a program or project.

Technical Performance Measures (TPM). A set of performance measures that are monitored by comparing the current actual achievement of the parameters with that anticipated at the current time and on future dates. TPMs are used to confirm progress and identify deficiencies that might jeopardize meeting a system requirement. Assessed parameter values that fall outside an expected range around the anticipated values indicate a need for evaluation and corrective action. Technical performance measures are typically selected from the defined set of Measures Of Performance (MOPs).

Technology Readiness Level. Provides a scale against which to measure the maturity of a technology. TRLs range from 1, Basic Technology Research, to 9, Systems Test, Launch, and Operations. Typically, a TRL of 6 (i.e., technology demonstrated in a relevant environment) is required for a technology to be integrated into a flight system. (See Systems Engineering Handbook NASA/SP-2007-6105 Rev 1, p. 296, for more information.)

Tightly Coupled Programs. Programs with multiple projects that execute portions of a mission(s). No single project is capable of implementing a complete mission. Typically, multiple NASA Centers contribute to the program. Individual projects may be managed at different Centers. The program may also include other agency or international partner contributions.

Training. Design and implementation of effective training methods and resources to maximize human retention, proficiency, and effectiveness to successfully accomplish mission tasks, properly operate, maintain, and support the system and mission.

User. Personnel who will operate, maintain, train, and support the equipment, system, or facility.

Validation. The process of showing proof that the product accomplishes the intended purpose based on stakeholder expectations. May be determined by a combination of test, analysis, demonstration, and inspection. (Answers the question, "Am I building the right product?")

Verification. Proof of compliance with requirements. Verification may be determined by a combination of test, analysis, demonstration, and inspection. (Answers the question, "Did I build the product right?")

Waiver. A documented authorization releasing a program or project from meeting a requirement after the requirement is put under configuration control at the level the requirement will be implemented.

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