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Implementation of Human Systems Integration Technical and Management Process for the Lunar Gateway Program

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Abstract

NASA recognizes Human Systems Integration (HSI) as part of the overall systems engineering and acquisition strategy for space systems. The Lunar Gateway Program is implementing HSI technical and management process across the lifecycle of the mission, as required by NPR 7123.1C NASA Systems Engineering Processes and Requirements, and led by the Gateway HSI team as required by NPR 8705.2C Human-Rating Requirements for Space Systems, now HEOMD-003 Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions. NASA has been using HSI principles for many years and has applied them to many of its previous human spaceflight Programs. As NASA returns to the Moon in a more sustainable manner, the Gateway Program is maturing the application of HSI by implementing it more visibly as part of Artemis, with guidance from the NASA/SP-20210010952 NASA HSI Handbook. This paper discusses how HSI is being implemented in the Gateway Program, challenges faced with its implementation during the development phase, and strategies/approaches used to overcome those. The paper also covers HSI implementation for flight systems, vehicle processing, and interfaces across the six identified NASA HSI Domains: human factors engineering, operations, safety, training, maintainability and supportability, habitability and environment. The goal is to provide an overview of the implementation process of HSI in the Gateway Program as an example for other Programs/Projects/Missions that are looking to implement HSI.

Keywords: systems engineering, human systems integration, operations, maintenance, habitability, training, safety, human factors, supportability, environment, Gateway, Artemis.

Nomenclature/Acronyms/Abbreviations

ACD	=	Artemis Campaign Development
ConOps	=	Concept of Operations
EHP	=	Extravehicular Activity and Human Surface Mobility Program
ESPRIT	=	European System Providing Refueling Infrastructure and Telecommunications
ERM	=	ESPRIT Refueling Module
GUI	=	Graphical User Interface
GW	=	Gateway
HALO	=	Habitation and Logistics Outpost
HEOMD	=	Human Exploration and Operations Mission Directorate
HITL	=	Human in the Loop
HLS	=	Human Landing System
HSI	=	Human Systems Integration
HSR	=	Human System Requirements
I-HAB	=	International Habitation Module
LED	=	light emitting diode
LEO	=	Low Earth Orbit
NPR	=	NASA Procedural Requirement
SE&I	=	Systems Engineering and Integration
SLS	=	Space Launch System
VSI	=	Vehicle Systems Integration

1. Introduction

NASA defines Human Systems Integration (HSI) as part of the overall systems engineering and acquisition strategy for space systems. NPR 7123.1C NASA Systems Engineering Processes and Requirements [1] defines HSI as: "An interdisciplinary and comprehensive management and technical process that focuses on the integration of human considerations into the system acquisition and development processes to enhance human system design, reduce lifecycle ownership cost, and optimize total system performance. Human system domain design activities associated with operations, training, human factors engineering, safety, quality, maintainability and supportability, habitability, and survivability are considered concurrently and integrated with all other systems engineering design activities."

HSI activities contribute to mission success, affordability, operational effectiveness, and safety of a Project, Program, or Mission. They enable system designers to understand and accommodate human capabilities and limitations in their interactions with hardware and software in the given environment [2].

NPR 8705.2C NASA Human Rating Requirements for Space [3], and now HEOMD-003 Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions [4], require the formulation of a HSI Team, and identifies NASA-STD-3001 NASA Space Flight Human Standards [5] as Type 2 documents that must be tailored for a given Program to meet human rating certification needs. Ignoring HSI early leads to increased costs later in the lifecycle to meet Human Rating criteria; decreased ability of crewmembers to perform required tasks; and risks to safety and human health.

1.1 Human Systems Integration Domains

NASA HSI Domains are provided in Table 1, as identified in NASA/SP-20210010952 NASA Human Systems Integration Handbook [6]. Overall HSI Domain integration oversight is essential to effective HSI implementation. Each Domain has the potential to affect and interact with the other Domains, making it critical to execute an integrated discipline approach.

Table 1. Definitions of NASA HSI Domains [6]

Domain	Definition
Human Factors	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.
Operations	Full lifecycle 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.
Maintainability and Supportability	Designing for full lifecycle and simplified maintenance and accessibility, reliability, optimized resources, spares, consumables and logistics given mission constraints.
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.
Safety	Implementation of safety considerations across the full lifecycle to reduce hazards and risks to personnel, system, facilities and mission.
Training	Design and implementation of effective training methods and resources to maximize human retention, retrieval and transfer, proficiency, and effectiveness to successfully accomplish expected and unexpected mission tasks, properly operate, maintain, and support the system and mission.

1.2 Gateway and HSI Relevance

Gateway will serve as a multi-purpose outpost orbiting the Moon to provide essential support for long-term human return to the lunar surface. It is a vital component of NASA's Artemis Campaign Development (ACD) and will serve as a staging point for deep space exploration. Artemis includes Space Launch System (SLS), Orion, Gateway, Human Landing System (HLS), and Extravehicular Activity and Human Surface Mobility Program (EHP).

NASA is working with Commercial Providers and International Partners to establish the Gateway, as seen in Fig. 1. Elements and modules that will make up the Gateway include Habitation and Logistics Outpost (HALO), Power and Propulsion Element (PPE), International Habitation Module (I-HAB), European System Providing Refueling Infrastructure and Telecommunications Refueling Module (ERM), Logistics Module, Airlock, etc. [7]

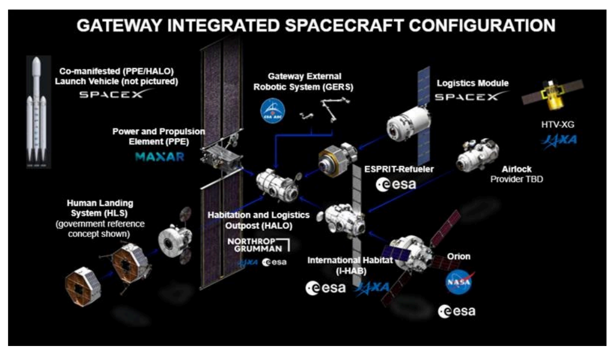

Fig. 1. Gateway Integrated Spacecraft Configuration [7]

HSI is a necessity to ensure mission success during crewed missions on Gateway. In addition to designing to provide an environment that will sustain crew health in cislunar space, the system must facilitate human interactions with complex systems developed by multiple providers to operate and maintain the vehicle, as well as to achieve science and exploration objectives. Incorporation of requirements and analyses intended to address these complex problems must begin early in the lifecycle. Known early key considerations that present design and operations cost challenges include solutions for exercise and food systems, provision of windows to meet crew needs, accommodation of daily working and living tasks in a limited habitable volume, and an approach to consistency in human interfaces across multiple modules and vehicles (e.g. Orion, HLS, HALO, I-HAB, ERM, visiting vehicles).

2. Implementation of HSI in Gateway

During formulation of the Gateway Program, the context of HSI in HEOMD-003 included a call out of the HSI Plan, a description of the HSI team, and their authority within the Program as part of the Human Rating Certification Package; as well as the frequency of the HSI Plan updates for the various NASA systems engineering lifecycle milestone reviews [3,4]. Unfortunately, not everyone involved in the development of HEOMD-003 was familiar with HSI, and it took a great amount of work for the HSI concept to be embraced. It was a worthy and value-add exercise educating various stakeholders on the unique value that HSI brings to NASA Programs and Projects. There were various presentations, discussions, illustrations, and lessons learned from operational spacecrafts that demonstrated the impacts to a Program/Project if HSI is not properly applied early in the lifecycle. Stakeholders appreciated and understood the comparison of HSI competencies to Systems Engineering & Integration (SE&I) competencies. Explaining the HSI Domains as listed in Table 1, describing how each HSI Domain affects and interacts with the others, and showing the architectural design and operations, was invaluable.

Once HEOMD-003 was updated with the appropriate HSI language and once Gateway was officially stood up as a Program, the next step was to develop a HSI Plan, HSI Charter, HSI Working Group, and form an HSI Team. While this may sound overburdensome or perhaps coming with a lot of overhead, purposeful strategies were put in place to start small and tailor HSI accordingly within the Gateway Program. This required extensive collaboration, open, and honest discussions between Program Management, HSI Lead, HSI Domain experts, Chief Engineers, Safety Engineers, Systems Managers, SE&I Offices, Project Teams, International Partners, and Commercial Providers. The goal was to right-size and minimally scale HSI for the Gateway Program; yet given the complexity of Gateway, ensure that all Module Providers were successful incorporating human capabilities and limitations into their design. Part of scaling HSI for Gateway was limiting the scope. Human in HSI refers to all personnel involved in a given system. Gateway HSI scope only covers flight crew, flight crew interfaces, and tasks performed by ground personnel that could affect flight crew. All other humans within HSI are bounded by current institutional procedures and processes.

One of the most critical and rewarding experiences of implementing HSI in Gateway have been the discussions with the International Partners and Commercial Providers. All have been very interested in learning what HSI is and how to implement and execute HSI within their organizations. The discussions have been educational. The discussions have been fruitful. The discussions have been hard. The discussions continue today. At this juncture of the Gateway Program, each Module Provider has incorporated HSI approaches into their design, while others have also expanded their workforce capability and organizations by hiring HSI Leads. The exchange of knowledge and collaboration has been the most rewarding part of HSI implementation and watching Module Providers take ownership of HSI. Knowing that the architectural aspects of the design have incorporated human considerations is key to ensuring the human's ability to successfully complete Gateway missions.

2.1 Human-Centered Design Approach

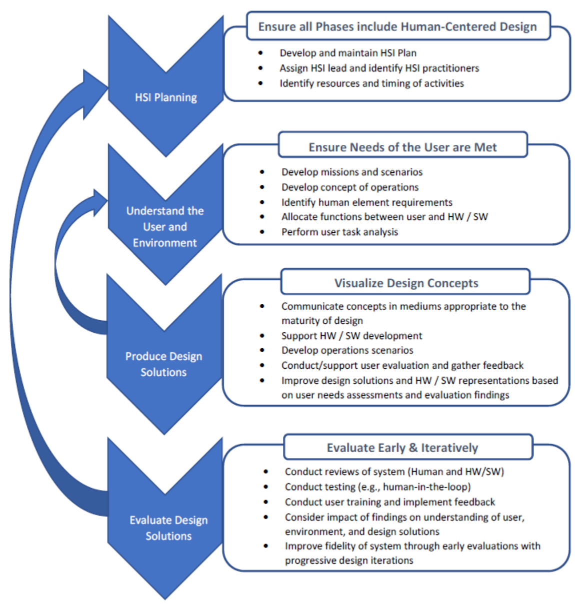

Fig. 2. Gateway Integrated Spacecraft Configuration [9]

HSI follows a human-centered design approach that requires an iterative and incremental development process in which partners and/or contractors assess HSI metrics throughout the development, realigning designs based on customer feedback and lessons learned from developmental testing. This approach is heavily driven by task analysis, leveraging an understanding of the tasks the operator must perform to drive design. Early assessments of human system interactions throughout design development are key to effective, efficient, and safe systems design, which reduces risks of design issues, unplanned costs, and verification non-compliance late in the design lifecycle. Fig. 2. depicts an adapted human-centered design approach based on NASA/TP-2014-218556 Human Integration Design Processes [8].

2.2 HSI Plan

Documentation of HSI implementation is required to ensure activities are being performed and all stakeholders are aware of their contribution to such implementation. This includes an overall Program HSI Plan as well as Project or Provider content specific HSI Plans that are updated at key points throughout the design process [9]. HSI Plan content is guided by the NASA/SP-20210010952 Human Systems Integration Handbook. It describes HSI methodology, tools, activities, and deliverables. The HSI Plan also defines how HSI is implemented across the Program with detailed organizational roles and responsibilities [6].

HSI implementation also involves incremental verification and validation activities, primarily through an iterative Human in the Loop (HITL) testing plan with user-representative participants performing planned tasks with flight-representative hardware, software, and procedures at increasing system fidelity [10]. This requires mockups and engineering simulators of workstations and spacecraft elements at appropriate levels of fidelity, which is defined through task analysis. These mockups and simulators, including virtual/augmented reality simulations, are also required later in the Gateway lifecycle for training activities. In addition to HITL testing, analyses and supporting verification activities may rely on examination of drawings; modeling (graphical, probabilistic, etc.); and use of virtual/augmented reality environments. To support the HSI technical development effort is essential to include operations subject matter experts in training and real-time spaceflight operations, in addition to astronauts with spaceflight, test flight and/or astronaut training experiences.

2.3 HSI Activities and Products in NASA's Systems Engineering Lifecycle

HSI activities and products are required for NASA and for contractors/partners, which are summarized in Table 2. These products and activities are defined in the Gateway Program HSI Plan [9]. Lessons learned are captured throughout the lifecycle of Gateway and are used to recommend changes across Gateway modules and Projects, and/or to provide actionable recommendations for other Artemis Programs and NASA standards and processes. Inherent in the ability to capture HSI lessons learned during operations is the inclusion of HSI as a stakeholder for Gateway operations, including the opportunity to capture HSI metrics and feedback throughout operation.

Table 2. HSI Activities/Products by Lifecycle Phase [9]

Lifecycle Phase	Phase Description	Activity, Product, Risk Mitigation
Pre-Phase A	Concept Studies	• Conceptualization and architecture • Contributions to commercial service procurement activities • Initiate HSI planning • Support feasibility activities • Contributions to development of operational concepts
Phase A	Concept & Technology Development	• HSI Plan • Human System Requirements (HSR) • Contributions to Program and subsystem specifications • HSI WG • Contributions to procurement activities • Trade studies in support of risk mitigation
Phase B	Preliminary Design & Technology Completion	• HSI Plan (baselined) • HSR (baselined) • Contributions to Program and subsystem specifications • HSI WG continues • V&V planning • Lessons Learned documentation (initial)
Phase C	Final Design & Fabrication	• HSI Plan (update) • HSR (update if appropriate) • Contributions to Program and subsystem specifications • First Article HSI Tests • HSI WG • Lessons Learned documentation (updated)
Phase D	System Assembly, Integration and Test, Launch and Checkout	• Validation of human-centered design activities • Validation of ConOps • HSI WG • Lessons Learned (updated)
Phase E	Operational Sustainment	• Monitoring of human-centered design performance • HSI WG
Phase F	Closeout	• Lessons Learned report

3. Challenges with HSI Implementation during Design Development

One of the basic challenges with HSI implementation is the fact that HSI is not considered an engineering discipline. Designers typically have the notion of iterative design and test and identify errors in the early stages of a Program/Project. Engineers typically design from first principles, design it properly the first time. It is not yet second nature to design hardware and software with human considerations and limitations in mind. Therefore, it takes time for organizations to understand and implement concepts and approaches to HSI. It takes deliberate execution of HSI to make it successful.

Other specific challenges to HSI implementation on Gateway include: Consistency and Standardization, Maintainability Standards/Performance Requirements, and Training Considerations/Training as a Single Point Failure, which are discussed in the next subsections.

3.1 Consistency and Standardization

The issue of consistency and standardization is prominent, especially for Exploration Missions beyond Low Earth Orbit (LEO). Given the various different acquisition strategies in-work for the Artemis campaign (Orion, Gateway, HLS, EHP), consistency among spacecraft and modules becomes imperative. Examples of some of the consistency issues between spacecraft and modules include: labeling, operations nomenclature, location coding, hardware controls, common tools and fasteners, hatch opening direction, graphical user interfaces (GUI), non-graphical user interfaces, crew restraints, cargo transfer bags, and mission support applications. If the current Gateway crew interface requirements cannot promote consistency across the different Gateway modules, there is risk of an increase in crew time required to perform tasks and an increased risk of human error during operations.

Solution in Progress: The risk of inconsistent crew interfaces across vehicles is now being worked in collaboration with the ACD SE&I Interoperability Working Group, and Gateway is leading some of the identified gaps/opportunities in standardization.

3.2 Maintainability Standards and Performance Requirements

A second challenge is with maintainability standards and performance requirements. The overarching philosophy was to levy minimal maintainability standards/performance requirements in order to empower Module Providers to make smart trades on maintainability versus reliability. This left Program level maintainability personnel having to embed themselves at the Project level in order to influence module designs and ensure they were included in important conversations/decisions.

Solution in Progress: A Maintainability and Sparing WG has been created, as a sister organization of the HSI WG to ensure the HSI Maintainability and Supportability Domain focused topics are well addressed. The frequent meetings between NASA and Module Providers has helped to discover some gaps, and continually improve Program insight/guidance.

3.3 Training Considerations and Training as a Single Point Failure

Another challenge is infusing training considerations early in the design process. Training for real-time operations should commence well before final hardware and software designs are completed in order to inform design. Assuming designs will work if the operator is well trained and will not make mistakes is not realistic. Physical and mental human capabilities and limitations should be taken into account during the design phase, and training as an HSI Domain should be infused early and not result as a single point failure.

Solution in Progress: There is a proposed update to NASA-STD-3001 and NASA HSI Handbook to specify training requirements during the design phase. There are continuous discussions regarding training needs with Module Providers and ensuring their HSI Plans include accountability for training considerations.

4. Strategies and Approaches to Implementation of HSI in Gateway

Gateway HSI strategies include the formation of a chartered Human Systems Integration Working Group (HSI WG), which was established to fill the role of the HSI Team required as part of the Human Rating Certification process [3,4].

4.1 HSI Working Group

The Gateway HSI WG provides a forum for discussion of HSI related topics with stakeholders from different NASA HSI Domains across the Gateway Program. These discussions result in integrated HSI recommendations presented to NASA Technical Authorities and Program Management to inform their decisions.

The WG defines and manages Gateway Program HSI activities and processes with in-line Gateway teams. It also coordinates and develops HSI driven recommendations regarding Program requirements, design, and implementation; develops and maintains identified HSI watch items and risks; and represents HSI interests in trade studies, technology down-selects, early phase simulations, model development, and HITL activities, providing recommendations for an integrated Gateway, modules, subsystems, and/or component levels [11].

The Gateway HSI WG has also taken an additional role to lead the Gateway HITL evaluations test readiness review process, in coordination with the Gateway Verification and Validation Team. This ensures successful coordination of joint HITL evaluations, where NASA participants are used as test subjects and/or evaluations are conducted at NASA facilities [10,12].

Module Providers have also opted to establish their own HSI WG, where NASA HSI stakeholders regularly attend based on agenda topics. These Project level HSI WG meetings help with discussions specific to modules to address interpretation of requirements, process, status, and coordination among internal provider subsystems, as well as for customer's awareness and prompt feedback to proposed design solutions.

4.2 HSI Team

The HSI Plan defines roles and responsibilities within the Program. HSI responsibilities cross organizational lines and must include participants across HSI Domains and Program functions. Table 3 shows an outline for HSI team members in the Gateway HSI WG. Notice that members include International Partners and cross-Program representatives to ensure interoperability and crew interfaces are consistent, and that impacts of Gateway decisions are also accounted for in designs of other Artemis Programs. Gateway has one more layer of complexity than other Programs, given the different modules that make up the outpost; hence the active participation of Module Provider representatives and Program system engineering managers/leads is crucial.

Table 3. Gateway Program HSI Team

HSI Domains Representatives • Human Factors • Training • Safety • Maintainability and Supportability • Operations • Habitability and Environment	**Gateway Technical Authorities** • GW Health & Medical TA • GW Engineering TA • GW Safety TA
Directorate Representatives • Human Health and Performance • Flight Operations • Engineering • Safety and Mission Assurance	**Program/Project Representatives** • GW Human Rating • GW VSI • GW SE&I • Systems Engineering Managers/Leads (system, subsystem, component)
Gateway Module Provider Representatives	**International Partners**
Cross-Program Representatives	**Ad-hoc Members**

4.2.1 HSI Lead Function

The Gateway Program has delegated the HSI Lead function to the Human Health and Performance (HH&P) Directorate Gateway Team. They are responsible for the development and maintenance of Gateway HSI documentation, including HSI Plan, HITL Evaluations Process, HSI WG Charter, and HITL Strategic Plan. In their HSI Lead role, HH&P Gateway Team is also responsible for the coordination of Gateway Program cross-team collaboration on HSI related items. HSI is by its nature a highly integrated discipline that cannot be approached standalone; thus, establishing relationships and communications plans with related teams and systems managers/leads is essential to a successful implementation of HSI.

4.3 Tracking of Risks

Gateway risk management is governed by its Gateway Risk Management Plan; there is not a unique risk process for HSI. In-line teams, through Technical Authority Delegates and/or Gateway System Managers, keep Gateway apprised of HSI concerns and potential Gateway risks. HSI issues are identified through reviews of subsystem design requirements, identification of deviations from requirements flowing down from Gateway level assumptions or decisions, reviews of lessons learned from Gateway and/or other NASA Programs, incident documentation, etc. HSI unique contributions to issues and risks take into consideration cost, schedule, safety, and trade-off concerns with the integration of human elements within the total system. Issues tracked are reviewed regularly at the Gateway HSI WG, and assessed if need to be elevated to a Gateway Program risk and/or that require Technical Authority attention. An example of an elevated risk not only through Technical Authorities and the Gateway Program, but also to the Artemis level, has been the consistency risk of crew interfaces across vehicles as stated in Section 3.

4.4. Frequent Communication of Decisions

Strategies to help deal with some of the HSI implementation challenges include implementing a more robust, methodical process for continuous changing Program/Project decisions. Ensure decisions made at the Project level are communicated up to Program level, and vice-versa, in a timely manner. Allowing flexibility and adaptability in the designs is an important acquisition strategy that should be honored, but with an implemented mechanism to ensure all system and Project teams have the opportunity to hear decisions and weigh-in at all levels of the Program. In addition, Programs need to ensure continuous improvement is captured as part of the Quality Management System, whether in the NASA side or on the Module Provider side, or both.

5. Conclusions

HSI activities enable system designers to understand and accommodate human capabilities and limitations in their interactions with hardware and software in the given environment. Ignoring HSI early on in a Program leads to increased costs later in the lifecycle to meet Human Rating criteria; decreased ability of crewmembers to perform required tasks; and risks to safety and human health. With the Gateway providing an environment that sustains crew health in cislunar space and with systems that must facilitate human interactions with complex systems developed by multiple providers, HSI was considered a necessity for this Program.

During the early stages of the Gateway Program formulation, it took some time and effort for the HSI concept to be embraced. Once embraced, the Gateway Program baselined a HSI Plan, established a HSI WG along with a charter, and an HSI Team was formed. So as to not be overburdensome and not require a significant amount of resources, purposeful strategies were put in place to start small and tailor HSI accordingly within the Gateway Program. The goal was to right-size and minimally scale HSI for the Gateway Program. This was done by limiting the scope of HSI for Gateway to only cover the flight crew, flight crew interfaces, and tasks performed by ground personnel that could affect flight crew.

HSI implementation for the Gateway Program certainly comes with challenges. It is not yet second nature to design hardware and software with human considerations and limitations in mind, and it can take time for organizations to understand and implement HSI concepts and approaches. Other HSI implementation challenges faced on Gateway for which we have solutions in progress include items such as consistency, maintainability, and training considerations. Gateway International Partners and Commercial Providers have been very interested in learning what HSI is and how to implement and execute HSI within their organizations. Having the current HSI technical and management processes and support in place, along with plans for assessing HSI implementation and making process improvements along the way, the Gateway Program is set up for successful missions. The Gateway is paving the way for HSI implementation of other Artemis Programs.

Acknowledgements

Thank you to the Lunar Gateway Program and the Human Systems Integration Team who have been key to the implementation of HSI across the Program and paving the road for other Artemis Programs.

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