Tailoring of NASA-STD-3001 to Lunar Gateway Program Requirements

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Abstract. The Gateway Program must meet NASA's Agency-level human rating requirements, which are intended to accommodate human capabilities and limitations while protecting the safety of the crew, and providing to the maximum extent practical, the capability to safely recover the crew from hazardous situations. Human systems integration represents a key human rating component of Moon to Mars systems to support the execution of Artemis missions, including compliance with mandatory standards for Health and Medical, Safety and Mission Assurance, and Engineering. The human system requirements, together with the human systems integration plan, medical operations requirements, and Gateway subsystem specifications, represent the flow-down of NASA Health and Medical Standards (NASA-STD-3001, Volumes 1 and 2) into the Gateway system. This paper discusses how these documents and other human systems integration activities provide full consideration of human capabilities and limitations as part of the total system design trade space, serving as an example on how the human must be effectively integrated as part of the system in order to achieve mission success. At a bigger scale, the paper contributes to the application of systems engineering standards to cutting-edge space exploration initiatives and to the dialogue on how systems engineering can continue to evolve to meet the needs of such ambitious projects.

Keywords. Systems engineering, systems integration, human systems integration, Artemis, Gateway, Moon, space exploration.

Introduction

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 Moon to Mars Program, hence the Artemis campaign, and will serve as a staging point for deep space exploration. The Moon to Mars Program includes the Space Launch System (SLS), Exploration Ground System (EGS), Orion, Gateway, Human Landing System (HLS), and Extravehicular Activity and Human Surface Mobility Program (EHP) (NASA, 2023). NASA is working with commercial providers and international partners to establish the Gateway. Elements and modules that will make up the Gateway include the 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, and Airlock. (NASA, 2022). Human Systems Integration (HSI) is a necessity to ensure mission success during crewed missions on Gateway. The systems must be designed to provide an environment that sustains crew health in cislunar space. The system must also facilitate human interactions with complex systems developed by multiple providers to operate and maintain the vehicle. Lastly, the system must allow for performing science and exploration objectives. Incorporation of requirements and analyses intended to address these complex problems must begin early in the lifecycle (Silva-Martinez, Etchells, & Bradshaw, 2023). Known early key considerations that present design, operations, and 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. This is managed by the Human Health and Performance (HH&P) Gateway Systems Engineering and Integration (SE&I) team, which has two main roles:

1) Lead Human Systems Integration (HSI) on behalf of the Gateway Program, and

2) Manage NASA-STD-3001 tailored requirements for Gateway Program in support of Health & Medical Technical Authority (HMTA).

This paper focuses on the second role for the tailoring of the standard into Gateway Program requirements.

Figure 1 shows the HEOMD-003 Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions at Level 0, which is needed in order to certify a system as acceptably safe to carry NASA crewmembers on deep space missions (NASA, 2021a). HEOMD-003 identifies NASA-STD-3001 Volume 2 as a Type 2 document that must be tailored for a given program to meet human rating certification needs, which is at Level 1 (2021b). Then, at the Level 2 is the breakdown of program specific requirements and where the identified HMTA requirements are addressed. The GP numbers represent Gateway Program (GP) documents. Level 3 and on are the documents that module and subsystem providers use to further derive their own design requirements. As shown in the green bubble of Figure 1, the Human System Requirements (HSR) are cross-cutting, which means that the requirements are applicable for design of any hardware or software with which the crew interacts, regardless of the subsystem responsible for implementation. The system is composed of the human, software, and hardware (NASA, 2023a).

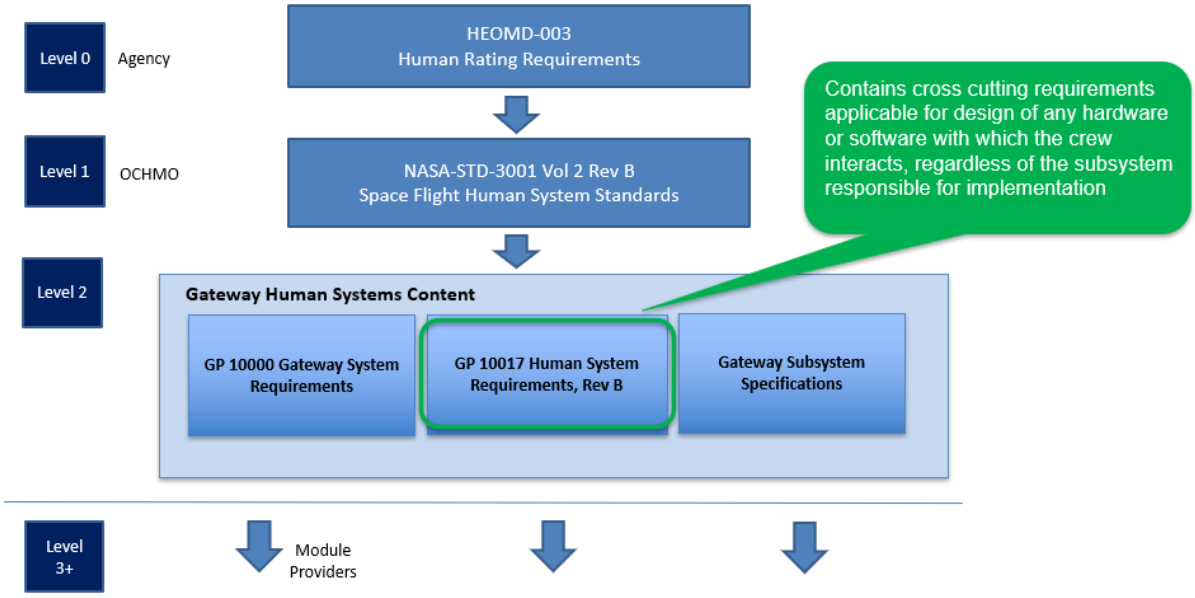

Figure 1. Flow of Requirements from NASA Standards to Gateway Requirements

Methods

The technique of tailoring specialized standards to specific program needs is a well-established practice in systems engineering and program management, particularly for complex and high-risk endeavors such as space exploration. As aspect that plays into tailoring standards is acquisitions and contracts. Given the unique program's mission parameters, standards living in the NASA-STD-3001 Volume 2 Revision B were selected as applicable to the Gateway Program. From there, customization and tailoring of those selected standards occurred to generate or modify specific program requirements.

Initially, two books for HMTA related requirements were under development. The first book included requirements where the expertise resided within the HH&P directorate, and the second book included requirements that were more fit for hardware and software books for a more efficient implementation. During the program specific requirements development, the second book of HMTA related

requirements were distributed across various subsystem specifications to ensure the hardware and software elements consider the human needs as part of their designs.

After the distribution of HMTA requirements across various program specifications, the HH&P Gateway SE&I team performed a detailed review to ensure the requirements were verifiable, allowed for meet the intent verifications where applicable, and remained flexible to keep refining them based on module providers feedback from their interpretations of the requirement language. The team worked heavily with the discipline subject matter experts as well as with the Gateway test and verification team to help develop strong verification methods, mechanisms, and success criteria. A close connection with the testing team is highly recommended as it helps the various subsystems identify their human in the loop (HITL) testing needs. This includes, facilities, people, tools, methods, mockup certifications, etc. which makes for a robust HITL strategic plan (NASA, 2021c; Silva-Martinez, et al., 2022). The HITL evaluations process is invoked by the Gateway Verification and Validation Plan (NASA, 2022a).

The tools used were Microsoft Excel, Dynamic Object Oriented Requirements System (DOORS), and SharePoint. Excel was used primarily for early stages of identification of standards and then for drafting requirement changes before they went out on change request (CR) process. Once approved, requirements were managed in the DOORS database. The development of verifications was done in SharePoint through a living tool that allowed for team collaboration, and once approved they were moved to the DOORS database.

Gateway Systems Requirements

Specific design performance requirements to meet Gateway's overarching functional requirements are detailed in the GP 10000 Gateway Systems Requirements (GSR) specification and various subsystem specifications. HMTA owns 22 requirements in the GSR that flow to multiple subsystem specifications. Most verifications of HMTA-owned Gateway requirements are audits of HSR and subsystem specification requirements. HMTA is also a co-owner of 20 requirements in the GSR. Co-ownership refers to requirements where other teams also have responsibility over the requirements and their verifications acceptance.

The HH&P Gateway SE&I team utilizes the trace from NASA-STD-3001 Volume 2 into tailored Gateway requirements to ensure the GSR overarching functional requirement will be met by requirements in HSR and subsystem specifications. In most cases, requirements in GSR do not have enough detail to meet a NASA-STD-3001 Volume 2 standard alone and need the requirements in other specifications to be met. The HSR specification is invoked by the GSR (NASA, 2024).

Human System Requirements

The HH&P Gateway SE&I team is the book owner for the GP 10017 HSR specification, which is divided into several sections:

- Anthropometry and Biomechanics
- Toxicological and Environmental
- Acceleration and Vibration
- Acoustics
- Radiation
- Architecture
- Windows
- Hazards and Safety
- Maintenance
- Crew Interfaces
- Decompression Sickness Treatment

The HSR establishes requirements and verification methodology to ensure proper integration of the human as part of the system across the Gateway Program. It represents a key component of human rating of exploration systems, including compliance with mandatory standards for Health and Medical,

Safety and Mission Assurance, and Engineering (NASA, 2023a). The HSR applies to all crewed mission phases identified in the Gateway Program Concept of Operations and Gateway Architecture Definition Document (NASA 2019 & NASA, 2021).

Figure 2 shows the requirement count as of February 20, 2024. As requirements merge, are decomposed, or moved, this breakdown may change.

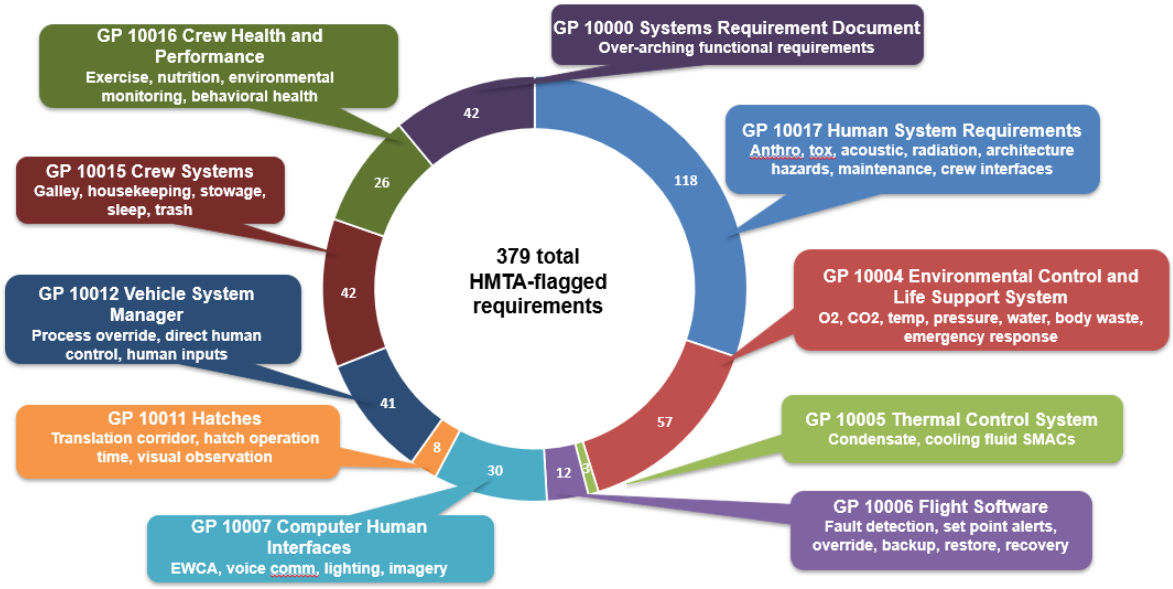

Figure 2. Breakdown of Human Requirements Across Various Gateway Specifications

Integration with Module Providers

Module providers designed either by commercial companies or international partners take the Level 2 requirements defined in the specifications mentioned above, as well as an allocations matrix provided as part of each document. They develop their own requirements and verifications at Level 3 and subsequent levels when using other suppliers. The HH&P Gateway SE&I team provides continuous guidance during the development of the modules' HSI Plans, products, and activities in support of their progress across their project's lifecycle reviews. Of great advantage for the module providers has been the dedicated human systems integration working groups and HITL evaluations process for joint tests worked in conjunction with Gateway's Verification and Validation team (NASA, 2021d).

Preliminary Design Review

The Gateway Systems Engineering Management Plan, a tailored version of the NPR 7123.1D NASA Systems Engineering Processes and Requirements, calls out the need for a Gateway Human Systems Integration Plan (NASA, 2023b, 2023c). This HSI Plan outlines the products and activities for each systems engineering design review with the associated success criteria (NASA, 2023d; Silva-Martinez, Etchells, & Bradshaw, 2023).

For Gateway's Preliminary Design Review (PDR), the HH&P Gateway SE&I team delivered a HSI Plan, HSR, HMTA requirements in the GSR, and HMTA requirements in ten Gateway subsystem specifications. Each of those requirements with their respective verification method, mechanism, and success criteria; as well as allocations for the different Gateway modules. HITL planning including both developmental and verification started and will continue working with module providers to define tests, facilities, responsibilities for verifications, and other resources needed. As the Gateway development

progresses, the HH&P Gateway SE&I has also been collecting lessons learned and sharing those with other Moon to Mars Programs, such as crew interfaces consistency and interoperability concerns.

Challenges and Solutions

One of the early challenges was the use of container requirements initially created to decrease the total number of program requirements and linking of similar requirements into container requirements. While this approach was useful for early requirements development, it became troublesome during verification writing and obscured the requirements traceability between levels. This approach was not unique to HMTA requirements, as other subsystem requirements were also affected. Thus, an extensive effort was done at the program level to remove the container requirements in the GSR. Similarly, the HSR baseline contained some parent-child requirements within the same document, which created confusion for both the module providers and the team addressing the inquiries. The next revision of the HSR document removed those internal traces and clarified the requirements language accompanied by their rationales and verification statements.

Another challenge has been with how to communicate the reason behind a requirement. While the rationale language was provided for each of the requirements including examples of significant incidents in human spaceflight and pointers back to the standard, some module providers did not necessarily look at the details in the rationale sections. The way the team addressed these nuances was by bringing up those rationale discussions to the requirement working groups, which helped educate reluctant participants and clarify questions for others.

As expected, the distribution of HMTA requirements across various program documents increased the challenge to manage them. Thus, to ensure the HMTA standards were properly flowed down to the different program documents, the following actions have been put in place. The HH&P Gateway SE&I team has an interface to each of the Gateway subsystem specifications where requirements tailored from NASA-STD-3001 are included. HH&P discipline integrator team members, support both Level 2 and Level 3, and are assigned to each subsystem specification. They are in constant communication with subject matter experts and book owners of subsystem specifications where the HMTA owned and co-owned requirements are spread out.

The HH&P Gateway SE&I team addresses systems engineering and integration principles by being involved in the lifecycle of requirements and their verifications. Involvement includes attending subsystem meetings, reviewing designs, bringing in experts, helping balance expert expectations and program cost, schedule, and cross-program integration. As mentioned in the introduction, the other team's role is to lead the Gateway Human Systems Integration Working Group, which includes experts from different disciplines both from NASA and module providers covering Level 2, Level 3, and sometimes Level 4 as needed (NASA, 2021d). This forum has been instrumental in various requirements discussions, such as common questions that module providers and project leads from Government Furnished Equipment (GFE) have had during implementation of requirements. In addition, the dialogue occurs between the implementers either at Level 2 or Level 3 with the requirement owners, and those who will be reviewing the verifications closure notices, which allows for fruitful exchange of ideas and decision velocity. Depending on the topic, these discussions have evolved into proposed changes of requirements, negotiations on verification methods and success criteria, early identification of potential risks, and awareness across the program following proper CR and Board processes.

Forward Work

The HH&P Gateway SE&I team will continue to manage the 379 HMTA owned/co-owned requirements across Gateway Program specifications, supporting both Level 2 and Level 3 with interpretation and implementation of requirements, design verification objectives, verification events, and eventually reviewing verification closure notices. This applies to the different systems engineering lifecycles of the modules that make up Gateway as well as NASA GFE projects, to ensure implementation of HMTA owned and co-owned requirements as part of the overall system.

The team's approach to addressing the specific needs of the Gateway Program through tailored human system requirements contributes to the Future of Systems Engineering (FuSE) by demonstrating how flexible, adaptable, and responsive systems engineering needs to be, especially in the context of complex and groundbreaking missions. It aligns with INCOSE's HSI Working Group by ensuring all design and engineering disciplines include human and socio-technical interaction and integration to enable system performance. It also aligns with Technical Operations (TechOps) by addressing the practical application of these systems engineering practices in a real-world high-stakes environment.

Conclusions

The Gateway Program is implementing NASA's Human Systems Integration technical and management process across its mission lifecycle: recognizing human capabilities and limitations to effectively and affordably integrate them with system design and development, enable better error management, reduce lifecycle ownership cost, and optimize total system performance. This paper described a focused and systematic approach to adapting and applying NASA-STD-3001 Rev B standards to the Gateway Program, which is a critical task in ensuring safety, efficiency, and mission success. Challenges and mitigation steps were discussed, showing that incremental improvements are needed in systems engineering, which goes beyond a checklist approach to standards application.

By detailing the process and considerations involved in tailoring NASA-STD-3001 for the Gateway Program, the paper contributes to the understanding of how systems engineering standards can be effectively adapted and applied to innovative and complex missions. This contributes to the broader systems engineering challenge of ensuring that standards and best practices evolve alongside technological and mission advancements.

The paper adds to the body of knowledge in systems engineering for space missions by providing a detailed case study of standard tailoring. It shows the specific considerations, processes, and outcomes of adapting human system standards to the unique operational context of the Lunar Gateway. The insights and methodologies presented in the paper can directly inform systems engineering research and practices, especially in the aerospace sector and other industries where human systems integration are paramount.

Acknowledgements

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Biography

Jackelynne Silva-Martinez, PhD has served as Human System Manager for the Lunar Gateway Program and HH&P Gateway SE&I Team Lead. She was also HH&P SE&I Lead for the Commercial Low Earth Orbit Development Program. Previously, she worked as Operations Planning Flight Controller for the International Space Station, Robotics Verification and Validation Test Operator for the Mars Science Laboratory, Antennas Mechanical Systems & Project Engineer for GPS III, and Assembly Test & Launch Operations Systems Engineer for commercial and government satellite programs. Jackelynne is currently serving as Artemis Mission Integrator in the Moon to Mars Program Exploration Operations Office and as NASA's Agile Community of Practice Lead.