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NextSTEP Habitat Risk Reduction for Gateway

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Abstract

This paper will provide an overview of the Next Space Technologies for Exploration Partnerships (NextSTEP) habitation prototype and test efforts, and how they provide risk reduction benefits to the NASA Gateway Program from multiple perspectives. The Gateway is envisioned as an outpost orbiting the Moon that provides vital support for a sustainable, long-term base for human return to the lunar surface, as well as a staging point for further deep space exploration. Implementation of this outpost will foster U.S. industry and international partnerships and enable multi-discipline utilization. In advance of formal establishment of the Gateway program, NASA has been developing campaign strategies, architectures, habitat systems, and subsystems through a number of targeted development projects. The NextSTEP-2 Phase 2 habitat contracts were awarded to five commercial partners to develop their concepts for a Gateway system and provide a high fidelity, full scale ground prototype for independent habitability testing. These partnerships provided valuable risk-reduction benefits to the future Gateway from multiple aspects to include: business and process; leveraging and stimulating commercial industry and technologies; innovative technology development and application; common standards and interface development and architecture; and systems/subsystems analysis. The partnerships were established through a Broad Agency Announcement (BAA) solicitation and contracting process which provides more flexibility in developing desired capabilities versus the traditional requirements driven acquisition. This foreshadows the Gateway acquisition approach. The NextSTEP contract work has enhanced the experience base of both NASA and its industry partners in design, development, and testing of space habitat systems, and is providing a foundation from the transition from a prototyping effort to an implementing program. Each contractor developed a different architecture approach incorporating diverse technologies along with the associated detailed lower level requirements, trade studies, and functional allocation to implement their concept. These activities are executed concurrently with NASA's internal reference architecture development and have provided additional aerospace industry expertise that informs – and in many cases – validates the NASA efforts. A consistently managed set of ground test evaluations occurs at the end of the contract, but the design process has allowed ongoing development to inform and evolve the Gateway architectural concepts through a series of design analysis cycles. The rapid prototyping and design cycles of the various concepts follow universal ground rules and assumptions driven by mission objectives. In addition, the industry partners' early review and inputs on draft common interfaces and standards have resulted in more robust and universally acceptable standards.

Keywords: Gateway, Habitat, Artemis, Lunar, NextSTEP, Commercial, Cislunar

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Acronyms/Abbreviations
Air Revitalization System (ARS)
Architecture Definition Document (ADD)
Augmented Reality (AR)
Broad Agency Announcement (BAA)
Contract Line Item Number (CLIN)
Computer-Aided Design (CAD)
Design, Development, Test & Evaluation (DDT&E)
Designed for Minimum Risk (DFMR)
Environmental Control and Life Support Systems (ECLSS)
European System Providing Refueling, Infrastructure and Telecommunications (ESPRIT)
Extra Vehicular Activity (EVA)
Federal Acquisition Regulation (FAR)
Ground Rules and Assumptions (GR&A)
Human Landing System (HLS)
Intelligent Health Monitoring System (IHMS)
International Deep Space Interoperability Standards (IDSIS)
International Space Station (ISS)
Justification for Other than Full and Open Competition (JOFOC)
Lockheed Martin (LM)
Master Equipment List (MEL)
National Aeronautics and Space Administration (NASA)
Next Space Technologies for Exploration Partnerships (NextSTEP)
Northrop Grumman Innovation Systems (NGIS)
Orbital Replacement Unit (ORU)
Oxygen Generation / Sabatier (OG/SA)
Power and Propulsion Element (PPE)
Power Equipment List (PEL)
Statement of Work (SOW)
Sierra Nevada Corporation (SNC)
Utilization Module (UM)
Urine / Brine Processors (UP/BP)
Virtual Reality (VR)
Water Processor (WP)

1. Introduction

The NASA Next Space Technologies for Exploration Partnerships Broad Agency Announcement (NextSTEP BAA) commercial partnership mechanism has become a key enabler for exploration architecture development through collaborative efforts between the NASA team and commercial entities. NextSTEP is a BAA with Appendices for developing space exploration technologies in many areas such as lunar Gateway systems, propulsion, crew systems, In-situ Resource Utilization, and Human Landing Systems. Contract awards resulting from the BAA appendices require the commercial entities to match government resources by a minimum percentage. This encourages use of internal research and development concepts or leveraging technologies from other lines of business. The first of these NextSTEP Appendices was Appendix A, which was released in early 2016 and resulted in six awards, focused on a crewed habitation system for placement in lunar orbit – as discussed in [1], NextSTEP Appendix A Phase 2. One of these awards went to Nanoracks for a study concept on converting a spent upper stage into a habitable system but did not result in an effort to develop a full-scale habitat prototype. The remaining five awards went to the Boeing Company, Northrop Grumman Innovation Systems (Orbital ATK at the time), Bigelow Aerospace, Lockheed Martin, and Sierra Nevada Corporation. It should be noted that the first four of these companies participated in the Phase 1 NextSTEP habitat study so they had a baseline architecture to leverage going into Phase 2. The focus of this paper will be on executing the contracts, risk reduction, lessons learned, and other benefits feeding directly into the Gateway program, and some general benefits from the ground test evaluations of the prototype Gateway concepts developed by these contractor teams in 2019.

2. NextSTEP Hab Phase 2 Context

To understand the impact of the NextSTEP Habitat Phase 2 activities, it's informative to consider both the timeline of the activities themselves as well as other NASA activities that contributed to the current lunar exploration architecture.

2.1 Phase 2 Timeline of Developments

During the execution of NextSTEP Habitat Phase 2 work, the contractor teams progressed through their own design process and milestones culminating in a Gateway-similar architecture and a ground prototype for evaluation, thereby demonstrating the key features and attributes of that architecture as discussed in [1]. Figures 1-5 below provide in-space depictions of each of the contractor's Gateway architecture concepts [3]. Notionally, each of those concepts include habitation capabilities for four crew members; a means to attach visiting vehicles including Orion, lunar landers, and logistics vehicles; a power and propulsion element; and an airlock and associated systems to allow astronaut EVA.

Figure 1 – The Sierra Nevada Corporation Gateway Concept (Credit: Sierra Nevada Corporation)

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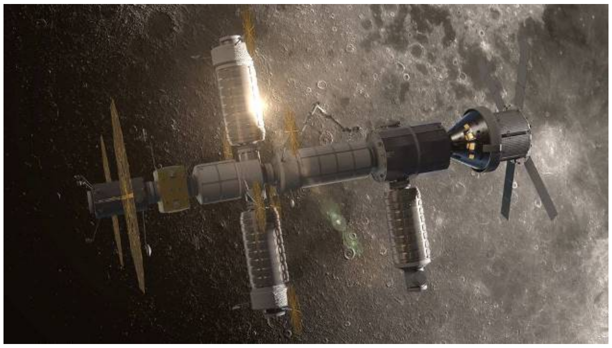

Figure 2 – The Northrop Grumman Innovation Systems Gateway Concept (Credit: Northrop Grumman)

Figure 3 – The Boeing Company Gateway Concept (Credit: Boeing)

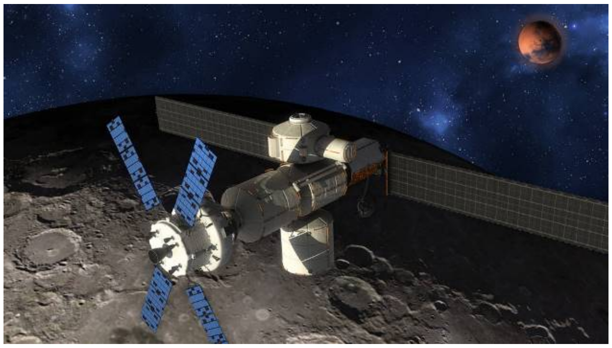

Figure 4 – The Lockheed Martin Gateway Concept (Credit: Lockheed Martin)

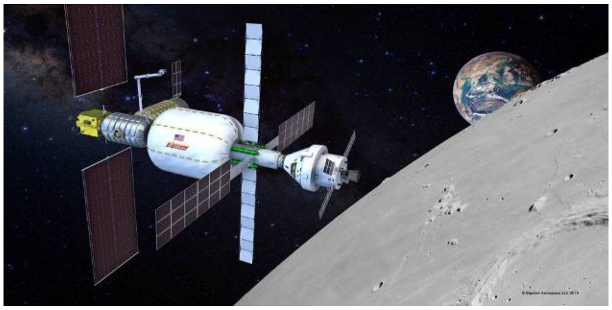

Figure 5 – The Bigelow Aerospace Gateway Concept (Credit: Bigelow Aerospace)

A NASA test team, including astronaut crews that would travel to the sites where the prototypes were housed, performed the tests and evaluations of those prototype habitats. The knowledge gained was not limited to habitability attributes from the prototype test results, but included additional insights into the design concepts and engineering analysis that were developed in the process. Additionally, the contractors developed other test assets and demonstrations that went along with the prototype evaluations. Images of the prototypes and test teams are included below in Figures 1-10. The five contractor prototypes were evaluated at the dates listed below:

- March 25-29, 2019: Lockheed Martin prototype evaluation completed at Kennedy Space Center, Florida.
- May 6-10: Northrop Grumman prototype evaluation test completed at Johnson Space Center, Texas.
- June 17-21: Boeing prototype evaluation test completed at Marshall Space Flight Center, Alabama.
- July 29-August 2: Sierra Nevada prototype evaluation test completed at Johnson Space Center, Texas.
- Sept 9-13: Bigelow prototype evaluation test in Las Vegas, Nevada.

Figure 6 - Astronaut crew training in Bigelow habitat module (NASA)

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Figure 7 - NASA and Bigelow prototype test team (NASA)

Figure 8 - Astronaut crew training in Lockheed habitat module (NASA)

Figure 9 - NASA and Lockheed prototype test team (NASA)

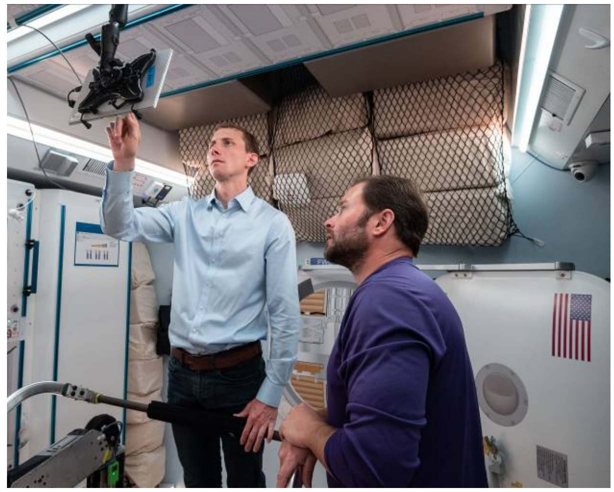

Figure 10 - Astronaut crew training in NGIS module (NASA)

Figure 11 - NASA and Northrop Grumman prototype test team (NASA)

Figure 12 - Interior of Sierra Nevada Corporation prototype habitat (NASA)

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Figure 13 - NASA and Sierra Nevada Corporation prototype test team (NASA)

Figure 14 - The Boeing Habitat Prototype (Boeing)

Figure 15 - The Boeing team inside the Boeing Habitat Module (Boeing)

After the conclusion of the Phase 2 prototype tests, the Habitat Element of the Gateway program – managed from Marshall Space Flight Center – plans to continue work to mature concepts for the Gateway, focused on a domestic habitat module. In August of 2019, the Habitat Element released draft requests for proposals for NextSTEP Habitat Phase 3 activities to progress habitat module concepts towards a System Definition Review (SDR) level of maturity module to Bigelow, Boeing, Lockheed, and Sierra Nevada Corporation. That work is planned for Fiscal Year 2020.

2.2 Significant Developments in Lunar Exploration Architecture

NASA has placed a high priority on a commercial partnering approach for the sustainability of future exploration architectures. As a result, the NextSTEP public-private partnership model is being utilized for development of elements of the architecture by releasing appendices of the NextSTEP Omnibus BAA.

As of the writing of this paper, there are currently 11 appendices of the NextSTEP Omnibus BAA as detailed on https://www.nasa.gov/nextstep:

- Appendix A - Habitation Systems
- Appendix B - Fabrication Laboratory (FabLab)
- Appendix C - Power and Propulsion Element Studies
- Appendix D - In-situ Resource Utilization
- Appendix E - Human Landing System Studies, Risk Reduction, Development, and Demonstration
- Appendix F - Trash Compaction and Processing
- Appendix G - Space Relay Partnership and Services Study
- Appendix H - Human Landing System - Integrated Lander
- Appendix I - Commercial Destination Development in Low Earth Orbit using the International Space Station
- Appendix J - Opportunities to Stimulate Demand in Low Earth Orbit through Applied Research
- Appendix K – Commercial Destination Developments in Low-Earth Orbit (LEO) Free Flyer

Of relevance here is Appendix A, which is the host mechanism for the Habitat Phase 2 work featured in the paper. Next chronologically in relevance is the June 21, 2018 announcement leading to Appendix C, which focused on studies supporting the eventual acquisition of the Power and Propulsion Element (PPE) which will provide power, orbital maintenance, attitude control, and positional location for the lunar Gateway. In February of 2019, Appendix E for Human Landing System (HLS) Risk Reduction was released. This appendix was focused on descent element, transfer vehicle element, and refueling element; the initial elements required for the full HLS. Together these appendices were focused on using a robust Gateway to enable crewed, sustainable lunar surface missions by 2028. This configuration included: a domestic habitat; an international habitat; a small pressured Utilization Module (UM); the European System Providing

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Refueling, Infrastructure and Telecommunications (ESPRIT); an external robotic arm, airlock and Extravehicular Activity (EVA) module; the Power and Propulsion Element; visiting vehicles of Orion to deliver the astronaut crew; and a logistics module to deliver supplies and equipment. In this scheme, the early priorities were on the first few missions establishing the PPE and the combination of ESPRIT and UM to be ready for the two Habitat modules. Finally, the airlock and EVA module would be added to complete the planned Gateway.

The early priorities were significantly changed on March 26, 2019 when Vice President Pence directed NASA to return humans to the surface of the moon by 2024 in a speech at the National Space Council Meetingin Huntsville, Alabama. That direction made it more important for the early Gateway to be able to support the HLS for staging and logistics supply.

As a result of the changing priorities, NASA jumped to Appendix H for the entire integrated HLS that will be utilized for crewed missions to the surface of the Moon. The first synopsis of Appendix H was released in April 2019, and a second draft was released at the end of August 2019 to prepare for the final request for proposals in the fall of 2019.

A significant Gateway milestone occurred on May 23, 2019 when Appendix C culminated in the selection of Maxar to deliver the Power and Propulsion Element of the Gateway, marking the first element of the lunar exploration architecture to be designated for a contract.

The work of Appendix A had a number of Gateway-type architectures from five different contractor teams, and provided NASA options for the early Gateway to accommodate the changing priorities. In July of 2019, NASA identified Northrop Grumman Innovation Systems (NGIS) as the company to build a small habitable volume as an addition to the PPE to form the early Gateway that would support HLS. NASA was able to reference the accomplishments from the NEXTStep Phase 2 work by NGIS for a Justification for Other than Full and Open Competition (JOFOC) that was announced on July 24, 2019 for this small habitable volume. The JOFOC announcement [2] indicated that future Gateway selections would be via “one or more of the existing contracts already in place via the NextSTEP-2 BAA Appendix A, Habitat Systems to further mature requirements and system definition leading to the Design, Development, Test & Evaluation (DDT&E) and delivery to NASA of a module for the NASA Gateway which must be launched late 2023.” The announcement indicated NGIS was the only NextSTEP-2 contractor with a module design and the production and tooling resources capable of meeting the deadline. Therefore, NGIS was selected to develop the small habitable volume, which has been designated as the Habitation and Logistics Outpost (HALO).

Additionally, because each of the five contractors in this Appendix A effort were looking at the entire Gateway architecture, their design concepts included not only the habitation module, but the aforementioned Appendix C PPE and other modules such as airlocks and logistics. The logistics concepts studied by the teams provided advanced preparation for a key enabler for the lunar exploration architecture. The Gateway Logistics Services (GLS) is being procured outside the NextSTEP Omnibus BAA approach as a separate but coordinated acquisition under the Gateway program. That solicitation was posted on Fedbizopps.gov on August 16, 2019 with contractor responses due in mid-October as of the writing of this paper. Each of the contractors in Appendix A had paid significant effort to envision logistics concepts for the Gateway with which they had the ability to draw from if they wanted to propose on the GLS procurement.

3. NextSTEP Hab Phase 2 Accomplishments and lessons learned

3.1 Gateway Design Influenced by NextSTEP Studies

In order to leverage the contractors’ architecture findings into the Gateway design approach, it was necessary that each contractor deliver sufficient data about their architectures for further analysis by NASA subject matter experts (SME). This data was provided to NASA in the form of an Architecture Definition Document (ADD), Master Equipment List (MEL), and Power Equipment List (PEL). Supplemental material was also provided via presentations at Technical Interchange Meetings (TIMs) for each design analysis or requirements analysis cycle. The information was given to NASA civil servant technical liaisons working with each of the contractors. The liaisons would ensure that the needed technical information for each contractor’s architecture design data delivered to NASA was sufficient for the needs of the agency. Additionally, the liaisons were able to integrate the technical data from each of the contractors and provide assessments, summaries, and presentations to NASA SMEs on the Gateway program. The assessments were compared relative to the NASA reference architecture.

The ADD is a comprehensive outline of technical content for the contractor’s architecture concept. It included element descriptions, system definitions, risk assessments, innovations, trades, analyses, and concepts of operation. This information was essential for informing NASA of each architecture’s benefits and risks to aid in procurement, adjusting NASA concepts of operations, solidifying interface requirements, and understand the ground support equipment and facilities required. Initially, contractors were asked to design an entire deep space cislunar Gateway using the elements mentioned earlier rather than just one element (e.g.

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domestic habitat). This allowed NASA to understand interface standards sensitivities, options for spreading functions across elements, and more possibility for innovations related to the integrated system. Later in the contract NASA requested later design cycles further narrow focus to the domestic habitat and logistics modules (if that was also a desired business growth area) and their related cost and SOW .

The Technology Needs Assessment section of the ADD identified key system technologies needed to enable the proposed mission concept and any development needed to buy down the technical and schedule risks of sending humans to deep space.

The commercialization plans highlighted aspects of the architecture and development that could be commercially viable for future businesses, allowing for NASA to protect those design spaces and processes for the development of a future deep space commercial industry.

In anticipation of the delivery of MELs from contractors, NASA developed a standardized format to assist in comparisons with the reference architecture and to fully understand itemized component lists for potential mass savings or growth (related to missing items). The Common Functional MEL template (CF-MEL) categorized items by functional disciplines within a hierarchy at the subsystem, equipment group, and component levels. When dealing with very different architecture designs from contractors, this capability enabled assessing performance characteristics more easily. These assessments were performed relative to the reference architecture to understand what performance factors were driving mass for each system, identifying any missing items, and noting any potential mass changes that could be leveraged from contractor innovations. With the combination of the context given in the ADD and the CF-MEL, teams could assess the fidelity of mass estimations relative to the planned functional performances. The process also gave insight into the refinement activities of the contractors by monitoring mass changes as the concept evolved with new analyses and trades. Reference to any mass offloading for later delivery that was required to make it within the launch vehicle capability could also be included within the CF-MEL notes. This in turn would inform the crew time models for assessing the required crew time for setup as this competes with other crew activities for missions. The challenge of launching habitats with the capabilities to support four crew for a 30-day period within the given mass constraints may require significant offloading. Offloading provided the opportunity for meeting the co-manifested SLS launch mass Ground Rules and Assumptions (GR&A) which was constrained to 8.5 metric tons for the SLS Block 1B. If other available launch and deployment options could be identified outside of the SLS Block 1B, this launch assumption could be relaxed. The CF-MEL was designed to be a standardized template that could be used across NASA contracts to assess proposed systems, with additional vetting and updates delivered during execution of the contract. This standardized common approach yielded a greater degree of robustness for the data and analysis processes. PELs were also provided by the contractors in order to clarify the power needs and potential gaps that will be compared as concepts develop further in Phase 3.

Finally, other important trade studies and assessments by the contractors were provided during TIMs occurring on a periodic basis during the contract period. Some of the risks, trades, and innovations identified in these meetings relating to thermal conditions, power profiles, designs, and concepts of operations were instrumental in educating NASA about the most appropriate design paths to pursue. Furthermore, these meetings raised awareness to SMEs of other design solutions and mitigations enabling greater safety and increased chance of success. The deep space environment has much different environmental concerns than in Low Earth Orbit (LEO), especially when operations are occurring over long periods and with significant quiescent states for vehicles.

3.2 Encouraging Commercial Innovation Through Use of High-Level Ground Rules and Assumptions

As part of the commercial partnering concept employed in NextSTEP Appendix A to mature the Gateway architecture, rather than work from detailed lists of requirements, a set of high-level GR&A was established to be able to allow flexibility and innovation in the contractor design. The GR&A captured architecture level assumptions, constraints, and functional and performance objectives, but avoided specifying design solutions wherever possible. To solicit innovation and alternative architecture approaches, the contractors had the opportunity to define their mission objectives, integrated architecture elements, requirements, approaches to risk, and functional objectives. Contractor teams could use the ground rules and assumptions to scope their designs, but they could also modify, adapt, and/or recommend changes by providing rationale and trade studies for diverting from the established ground rules and assumptions. Additionally, during the milestone reviews, contractor teams would consolidate questions and recommendations on the GR&A, and the NASA Integrated Architecture team would assess those inputs and provide feedback as appropriate to the contractor teams. Periodic updates were made to those GR&A as a result not only of the contractor inputs but also as maturation from the NASA architecture informed updates. In parallel with the contractor Phase 2 efforts,

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NASA proceeded with design analysis cycles for its own reference architecture. NASA minimized sharing the reference architecture and lower level requirements with the contractors to reduce influencing the commercial solutions and driving them all toward the NASA reference architecture. This approach resulted in more diverse concepts fulfilling the Gateway mission and allowed and encouraged the contractors to leverage technologies from other lines of business where economies of scale or prior investment of non-recurring engineering could provide capabilities more quickly and/or at lower costs.

3.3 Managing Contractor Concepts Relative to NASA Architecture

Throughout execution of the two parallel NASA and commercial partner efforts, a technical team of NASA analysts and subject matter experts assessed the trade studies, designs, and concepts from both efforts. The technical team created many opportunities for informing the NASA reference architecture and requirements effort with trade study results or issues reported by the contractor efforts. Among the many topical assessments the technical team provided to the architecture team were: volume allocation comparisons and concepts for outfitting secondary structures, mass analyses, PPE assessment in context with contractor architecture, functional allocation analyses, power assumptions and loads on systems, micrometeoroid orbital debris (MMOD) handling, thermal systems and analysis (including transit/deployment of habitat systems), leak rate analysis, payload accommodations, and others These assessments provided the effect of either defining the variability of the design space for a given capability, validating NASA findings, or illustrating where teams had incomplete understanding of technical implementation needs. The contractor findings were summarized to the NASA Gateway team through design briefings.

One of the key tasks assigned to the contractors was to assess and provide feedback on draft International Deep Space Interoperability Standards (IDSIS). Comments were solicited for whether the standards were appropriate, drove cost, schedule or risk impacts, had commercial or internal company alternatives, etc. The feedback from industry provided tremendous value to NASA and international partners in establishing many of the standards that will be embedded in specifications and requirements and familiarized industry with them in advance to the point of influencing them during their own design cycles. This same practice is being employed for other NextSTEP Appendices to ensure NASA and the development contractors reach a common understanding of application of standards.

The efforts of the contractor teams to create an integrated architecture that could be implemented with the limitations and challenges of the deep space environments and transit concerns brought a better understanding to NASA and contractors of the integrated performance level of limitations and constraints. Pursuing designs for only a subset of the larger integrated architecture would not have yielded the same degree of comprehensive understanding.

3.4 Contract Flexibility Advantages

NASA chose to use a BAA acquisition instrument for deep space exploration technology development for several reasons with all of them resulting in tremendous contractual flexibility. Flexibility is a key necessity when executing research and development contracts. A BAA (FAR 35.016) is a notice from the government that requests basic or applied research proposals from private firms concerning certain areas of interest to the government [4]. Use of a BAA is appropriate and encouraged when varying technical/scientific approaches can be reasonably anticipated, the government desires new and creative solutions advancing the state-of-the-art or increasing knowledge or understanding rather than focusing on a specific system or hardware solution. It provides flexibility in that it focuses on objectives in terms of areas of need or interest whereas using a conventional SOW and specific requirements could unintentionally stifle ideas and concepts. Appendix A provided the contractor the opportunity to develop their own statement of work and approach toward meeting the high-level GR&A. In addition, the evaluation process can be streamlined relative to a more conventional best value approach since it is to be based primarily on a peer or scientific review. The soliciting organization has more latitude for selecting proposals matching technology development gaps or needs, risk profiles, or funding availability in its portfolio, For Phase 2, NASA requested the contractors to submit their proposed efforts organized into Contract Line Item Numbers (CLINs) and contract options. By using this approach, the government and contractor had even more flexibility in selecting which CLIN efforts to execute and had options for adding work later. Additionally, the NextSTEP Habitat development effort was originally envisioned to be a phased approach from studies that would lead to flight hardware from the very start. As a result, the end of each phase required the contractor to submit a plan with SOW, deliverables, schedules/milestones, and price estimates for the next phase of development. This approach has proved to be very valuable to both NASA and the contractors because it inserts opportunities to assess progress, adjust acquisition or technical strategy, resynchronize approaches, and prepare both NASA and the contractor for the next phase of effort.

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The phased approach ended up paying significant benefits back to NASA when the decision was made to leverage the NGIS's contract and their Phase 2 work to develop the HALO on an aggressive schedule.

3.5 Life Support System Maturation

During Phase 2 NASA also investigated a modular approach to the Environmental Control and Life Support Systems (ECLSS). NASA coordinated direct collaboration between another contractor maturing that design with the Appendix A Phase 2 contractors to facilitate integration and optimization of that system for their architecture concept.

3.5.1 Consolidation of Life Support System Maturation

In addition to studies providing habitable volume for crew and logistics, the NextSTEP Appendix A solicitation sought studies for enhancements and testing of deep space habitation systems such as Environmental Control and Life Support Systems (ECLSS), including atmosphere revitalization and monitoring, water processing, lighting, and fire detection. An award was made in this area to Collins Aerospace for NextSTEP Modular ECLSS to develop concepts that group ECLS systems into packaged units maximizing the use of common components and the development of unique methods and design concepts that support in-flight maintenance and repair. The primary focus of the Phase 2 effort was to continue the development of a Universal Pallet Structure, an Integrated Modular Control Architecture, In-flight Maintenance concepts, and an Intelligent Health Monitoring System. [7]

A key component to the Modular ECLSS effort was regular integration meetings between Collins and the habitat contractors both individually and in town hall settings. This integration effort was intended to ensure that the resultant ECLSS modules were adaptable to the broadest range of habitable volumes and configurations under consideration by the habitat developers. The integration effort provided valuable feedback that Collins leveraged to improve the adaptability of the modular ECLSS system into the habitats. Most habitats adopted the Collins' Modular pallets as their ECLSS baseline. Some habitat contractors chose to maintain a separate ECLSS baseline to either highlight alternate technologies or customized packaging schemes suited to their habitat configuration.

3.5.2 Universal Pallet Structure

The Universal Pallet Structure enables pre-integration and checkout of ECLSS systems prior to installation into the habitat volume which also enables on-orbit outfitting to optimize launch mass or integration into deployed habitats. To achieve this, the pallet cross-section was sized to translate through an International Docking System Specification (IDSS) hatch diameter and the length was determined via virtual translation using the smallest habitat to establish a usable translation envelope. The ECLSS functions were aggregated into functional groups (Air Revitalization System (ARS), Water Processor (WP), Oxygen Generation / Sabatier (OG/SA), and Urine / Brine Processors (UP/BP)) where each functional group was packaged into multiple Universal Pallet Structures. The pallet was designed to withstand conservative launch loads to maximize flexibility in launch ConOps. To improve maintainability, the pallet offers front access and pivots on its front mounts to ease installation and maintenance which allows fluid, power, and signal interfaces to remain connected to the habitat during deployment. [7]

Refinement of the pallet and packaging is anticipated to continue. While maximizing flexibility, sizing the pallet structure to handle the most conservative launch loads comes with a structural mass penalty. In the case of on-orbit outfitting, this mass penalty carries over into systems that no longer require the load carrying capability. One area to explore is the decoupling of the structure required to survive launch loads from that needed to support on-orbit loads. With this approach, the launch carrier structure can be left in a logistics delivery vehicle instead of being transferred to mass-challenged exploration systems intended for Mars and beyond.

In dealing with the variation in habitat configurations in the NextSTEP Appendix A activity, it was realized that a one-size-fits-all ARS may not be optimum. Although the sensible and latent loads of the four crewmembers remain constant no matter what habit they are in, habitat size can drive variations in the required loads. For example, larger habitats have the potential to hold more equipment, which can increase the sensible heat load imparted to the air, and larger habitats have greater circulation flow requirements to maintain minimum velocities for mixing. Therefore, another area of continued work is to explore the interface of habitat ventilation systems with the ARS thermal and humidity systems to better address the adaptability of the ARS to multiple habitat configurations.

3.5.3 Integrated Modular Control Architecture

The Integrated Modular Control Architecture employs common computational modules distributed among the function groups where the memory and data resources are shared to minimize mass and power. The Functional Group Controllers contain the detailed control logic for each functional group. Data Distribution Services (DDS) middleware enables publish-and-subscribe networking between hardware and controllers. Control functions are deployed in a hierarchical fashion, emulating hardware topology. The

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system behaves as an Internet of Things with an independence and redundancy that is far more resilient than the current Federated System used aboard ISS. [7]

3.5.4 In-Flight Maintenance

In-flight Maintenance is a key enabler for future exploration missions since the current ground-supported Orbital Replacement Unit (ORU) remove and replace strategy is infeasible simply due to the mass of spare ORUs alone. [5] Under this effort, component grouping was re-envisioned into assemblies named “Maintenance Units” (MUs) because they are specifically identified and designed with in-flight maintenance in mind, something that legacy ORUs did not take into consideration. MUs are designed to be removed from the system, taken to a workbench, and repaired by fixing or replacing smaller subcomponents. The advantage is that the whole MU does not need to be replaced because of a faulty subcomponent.

Several design principles were established that maximize the maintainability at the System, Maintenance Unit, and Component levels. [6] For example, items that are not prone to failure (e.g. designed for minimum risk (DFMR)) or do not require servicing should be packaged out of the way, while serviceable items should be packaged for maximum accessibility. The commonality of components, fasteners, and seals should be maximized to limit required tooling and minimize sparing. Test points should enable isolation of faults to specific MUs. MU components should be aggregated onto trays or racks for ease of removal and all connections should face toward the unit access (e.g. a removable front panel). Quick disconnects (QDs) should be used for fluid connections that contain a hazardous fluid. Alternatively, non-hazardous fluid interfaces should use standard Army-Navy (AN) fittings for reliability and weight savings. The electronics and mechanical elements of components should be modularized and segregated to allow for independent removal and replacement without breaking connections unnecessarily.

3.5.5 Intelligent Health Monitoring System

An Intelligent Health Monitoring System (IHMS) is an essential constituent of the in-flight maintenance strategy. [7] It identifies early trends to improve maintenance planning and it isolates faults to components within specific Maintenance Units to ensure that maintenance actions address the root causes. Several implementation strategies were explored before selecting a Bayesian Network (Bayes Net) based IHMS. A proof-of-concept Bayes Net was developed using dynamic physics-based simulations of the ARS to demonstrate disambiguation of injected faults into an ARS fan motor. The Bayes Net-based IHMS was able to discriminate between different failure modes to isolate failures; however, increasing the quantity of training data and increasing the data sampling and storage rate will improve results. Though limited in scope, the effort was an important proof-of-concept that highlights the potential role of intelligent systems in improving the health monitoring of future habitation systems.

3.6 Supplemental Efforts to Augment Contractor Expertise

NASA leveraged expertise available within the agency in many areas to augment contractor capabilities in those areas. Notable subject areas featured within this paper are windows material database, inflatable structure materials performance, and VR and AR approaches developed for ISS.

3.6.1 Windows Material Database

During the NextSTEP Appendix A efforts, a windows materials database was developed by NASA windows materials experts and was provided to the contractor teams as a design reference. This database provided mass properties, environmental performance parameters, and optical quality to allow alternatives to traditional optical quality glass designs. Getting access to NASA experts was necessary for understanding the design process and implications of windows on current contractor concepts. Especially important was the need to integrate these structures into inflatable habitats while maintaining the seals of the air barrier. Resulting designs challenged the idea of using windows rather than camera systems that project the exterior view on interior walls instead. While using camera and interior projection systems seems like a viable replacement for windows, there are those in the habitation systems community that value a real viewing capacity as is familiar in day-to-day life. Alternate camera and projection systems also have different vulnerabilities and failure modes from more conventional windows. While windows on a habitable volume seem like a simple prospect, when windows are combined with other needs of the system, it often may result in very small viewing ports as implemented on older exploring versions of submarines. Many other things compete for space on the exteriors of habitable systems resulting in this final outcome. Soft goods structural designs often come with the additional challenge of integrating the windows with the soft goods system without creating additional leak areas. To further complicate the issue, the desire to have two radial docking ports and two axial ports on the habitat reduce additional surface area. While NASA has not become firm on window requirements, the agency has invited contractors to improve on these approaches while understanding particular design constraints, innovations, and risk mitigation. While the debate for and against windows continues, astronaut crew members have been given the

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chance in ground tests to evaluate both installed windows and the alternate projection concepts presented by contractors that opted against windows.

3.6.2 Structural Softgoods Assessments

Two contractors proposed inflatable habitat design concepts. These habitats have the advantage of much larger volumes, approximately 300 m^3 versus approximately 70 m^3 metallic structures with comparable masses. While these habitats offer greater volume, they remain a new structural technology for space applications that requires additional testing over metallic habitats, especially because these structures use materials with typically non-linear, load history dependent behavior and multiple unique factors that influence the structure in each stage of production, delivery, and storage. Flight heritage does exist for these structures and one such system is currently attached to the ISS: the Bigelow Expandable Activity Module (BEAM). The newer larger and more capable designs being developed differ not only in size, but structure and geometry (barrel section length, end cap slopes, etc.), thereby requiring new verification of structures becomes necessary. The design, testing, and certification of such structures for human-rating requires a thorough knowledge of the unique mechanical behavior and fabrication processes used.

NASA has developed standards for inflatable structures similar to standards for metallic structures used in habitable systems to ensure their overall safety. These standards have largely been developed while working closely with contractors who are developing these technologies and inflatable softgoods experts at NASA. During Phase 2 of the NextSTEP contract, NASA drafted a Soft Goods Requirements Handbook and has been soliciting input from those companies on the contracts that are designing, developing, testing, and evaluating them. The purpose of the handbook is to specify the minimum set of requirements that allows the evaluation of a crewed softgoods structure, including the salient fabrication, test, and analysis areas. The handbook includes the required material testing, component testing, and article level testing to evaluate the structures for safe habitability. Additionally, the handbook lists the required data and documents necessary for demonstrating the company's quality assurance processes, and verification and validation plans and outcomes. For the realization of a crewed softgoods structure, the hand book requires careful selection and statistical characterization of the softgoods materials and components, a robust and repeatable fabrication process, and a systematic and comprehensive test program that validates the performance of the design from component to full-scale article at a level consistent with human-rated spaceflight.

3.6.3 VR and AR approaches and applications

Work being done at NASA on VR and AR for ISS missions was leveraged to assist, augment, and increase collaboration in simulations with contractor efforts. This included some lessons learned from work at NASA as well as giving access to some of the NASA models and software applications used to make conversions from engineering CAD models into the VR environment in an optimized fashion. Additionally, the expertise of the NASA team working on these for ISS was able to assist with any questions that the contractors had. Several of the contractor teams used this opportunity to assess the benefits and limitations of using VR and AR in their design process and for operations. This, as an operational approach, was an important step for understanding the habitat concepts in a zero-gravity environment when most crew interaction on the ground test days were primarily working in one-g variations of the ground habitats, which created limiting conditions relative to the full zero-g experience of access to the volume and systems. It is also the VR/AR type environments that have been used to do crew training on orbit and may be extended to other deep space exploration situations, thereby allowing impromptu training situations for anomaly resolutions. In addition to using VR & AR for operational applications, several teams assessed using VR during the design and development phase to perform early integrated assessment of their designs. Using VR/AR was also effective in enabling visualization of a more complete integrated Gateway stack with the habitat ground prototypes in full scale.

3.7 Design and Test Process with Multiple Partners

The NextSTEP BAA model for developing and evaluating multiple habitat concepts to help mature the architecture for flight brought many benefits. The habitat design fidelity varied between contractors, but in general it was a higher fidelity than training hardware but less than an engineering or qual-level equipment with the higher-fidelity items centering around crew-equipment interfaces. The contractor teams were able to showcase their innovations and have their habitat's interior design approach evaluated by both crew and – for some systems – SMEs – if the fidelity was sufficient. Most of the contractors used their architecture studies to more accurately inform their habitat interior designs and volume allocations.

With five partners and five different corporate strengths, NASA was able to get diversity in proposed solutions to meet the ground rules and assumptions. The vendors all received valuable NASA feedback and guidance specific to their designs and approaches, and when asked, NASA was able to help them improve their design elements and capabilities which could help

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streamline the flight design process and potentially save money later. This rapid prototyping-like approach enables multiple system teams to address gross-integration issues during the pre-phase A and phase A stages allowing for a more effective and strategic design approaches going into SDR which could lower schedule risks and ultimately shorten the delivery time for flight articles. Feedback from NASA program management, contractors, and NASA Gateway stakeholders has been good and this model has been utilized in the efforts of other NextSTEP BAA appendices, including the approach for the HLS.

4. Conclusions

In conclusion, the NextSTEP Appendix A Habitat Systems Phase 2 architecture, prototyping and test efforts have yielded many lessons learned and benefits for both NASA and industry. It provided an opportunity for commercial partners to propose and develop innovative concepts leveraging their commercial and core competencies that can fulfil NASA requirements and for NASA to learn about diverse, alternative approaches toward establishing a lunar outpost. This paper documents a portion of the activities conducted and captures some of the lessons learned and benefits from the Appendix A Phase 2 activities that can be applied to other NextSTEP BAA Appendix efforts.

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References

[1] T. Gill, R. Gordon, E.C. Moore, S. Shull, M. Ching. A Novel Approach in Public Private Partnership Execution with NextSTEP-2 Habitat, AIAA Space 2018 Conference and Exposition, Orlando FL, 2018 17-19 September.

[2] Gateway Program Module(s) Continued use of NextSTEP-2 Broad Agency Announcement (BAA) Appendix A, 19 July 2019, https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=36ebf3fc4d57c88b6bd8c94d1806dfb9&_cview=0, (accessed 23.09.19).

[3] NASA Begins Testing Habitation Prototypes, 17 March 2019, https://www.nasa.gov/feature/nasa-begins-testing-habitation-prototypes (accessed 23.09.19).

[4] M. Ching, C. Zavrel, E. Mahoney, K. Becker, J. Crusan. NextSTEP Broad Agency Announcements; Overview. pp. 2-3. Briefing to multiple NASA audiences. August 2019.

[5] A. C. Owens, O. L. de Weck, C. Stromgren, K. Goodliff, W. Cirillo, "Accounting for Epistemic Uncertainty in Mission Supportability Assessment: A Necessary Step in Understanding Risk and Logistics Requirements", 47th International Conference on Environmental Systems 16-20 July 2017, Charleston, South Carolina, ICES-2017-109.

[6] J. A. Rohrig, J. O'Neill, & T. J. Stapleton, "In-Flight Maintenance Design Philosophy for Gateway and Deep-Space Life Support Systems", 49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts, ICES-2019-305.

[7] J. O'Neill, J. Bowers, R. Corallo, & M. A. Torres, "Environmental Control and Life Support Module Architecture for Deployment across Deep Space Platforms", 49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts, ICES-2019-308.