OPEN LUNAR FOUNDATION

Payload(Bay) X: A Modular Approach to Sustainable Lunar Operations

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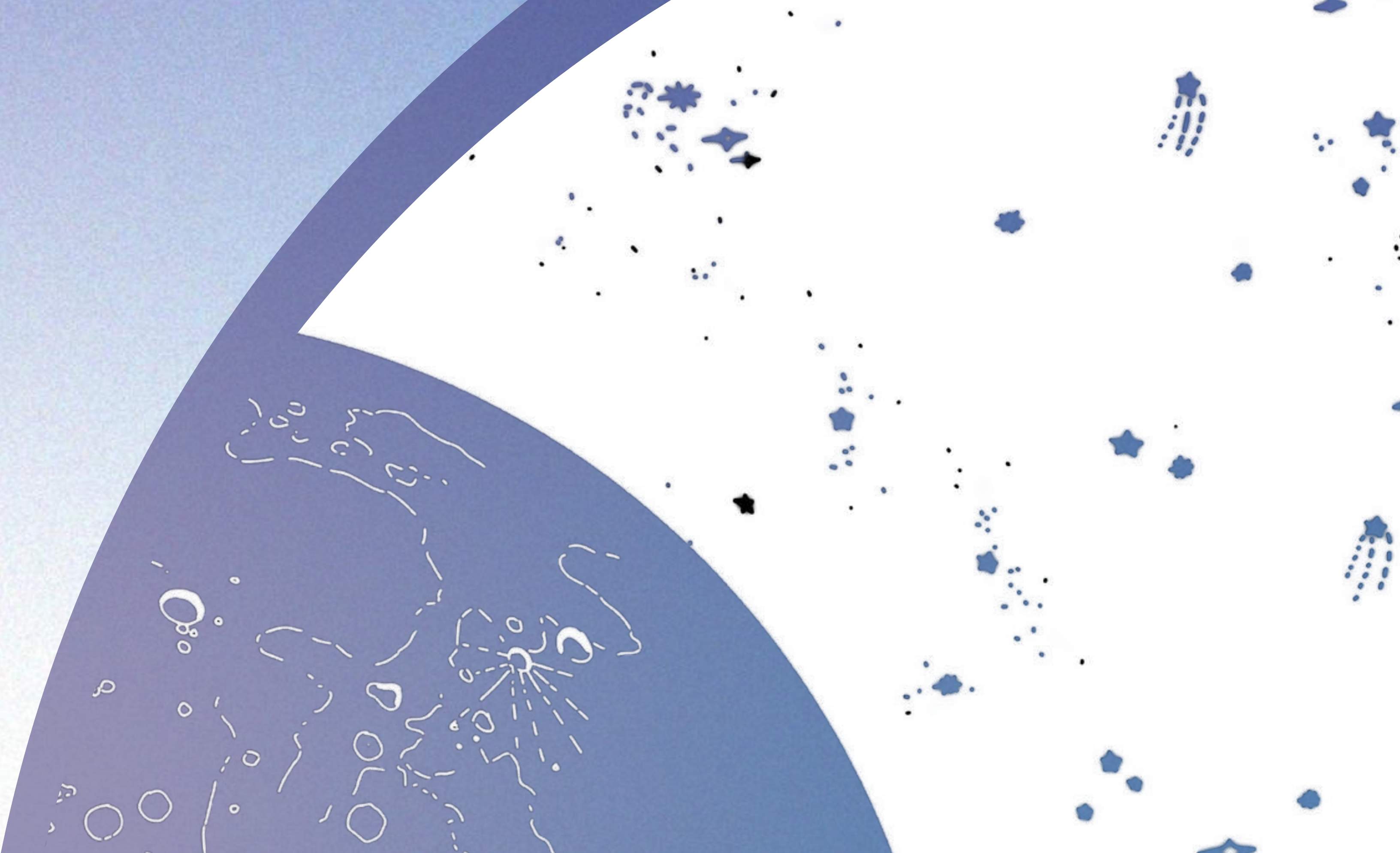

Abstract

This paper explores the potential of the Payload(Bay) X concept to advance progress towards sustaining a permanent human presence on the Moon. With a focus on critical life support systems for air, water, and food, the research identifies the key challenges and requirements for long-duration lunar missions. Current approaches to integrating life support technologies within lunar habitats face limitations in terms of cost, safety, and operational flexibility. The Payload(Bay) X concept proposes a modular external platform that enables more efficient testing, development, and implementation of these systems separately from the primary living quarters. Through quantitative analysis, the paper demonstrates the technical and economic advantages of this approach, including reduced development costs, improved hardware reproducibility, and increased flexibility for in-situ resource utilization. The research also outlines a roadmap for future work, including key next steps for further development and testing of the Payload(Bay) X concept. By addressing the challenges of sustainable resource management, this paper presents a promising pathway towards enabling long-term human presence on the lunar surface.

Introduction

As our human footprint on Earth increases, many are looking to the Moon and other celestial bodies for future habitation. Designing living environments off-world, or even on spaceships, can teach us valuable lessons about being more mindful and sustainable in how we use our limited air and water resources on Earth. Space habitats, with their relatively small sealed systems, provide solvable examples of how we can optimize resource utilization for a better future. In an extreme environment with limited resources, how we learn to survive and thrive can be massively uplifting for a range of socio-demographics on how to build towards a better future.

In 2014, a workshop called the Low Cost Lunar Workshop (LCLW) identified the cost and requirements to establish a long-term, permanent lunar presence (Harper et al. 2014). Building on this, the Open Lunar Foundation revisits the LCLW findings within the Payload(Bay) X topic area. This research explores how a modular external payload platform could advance progress towards sustaining a lunar presence by unlocking critical resources, with a focus on life support systems for air, water, and food.

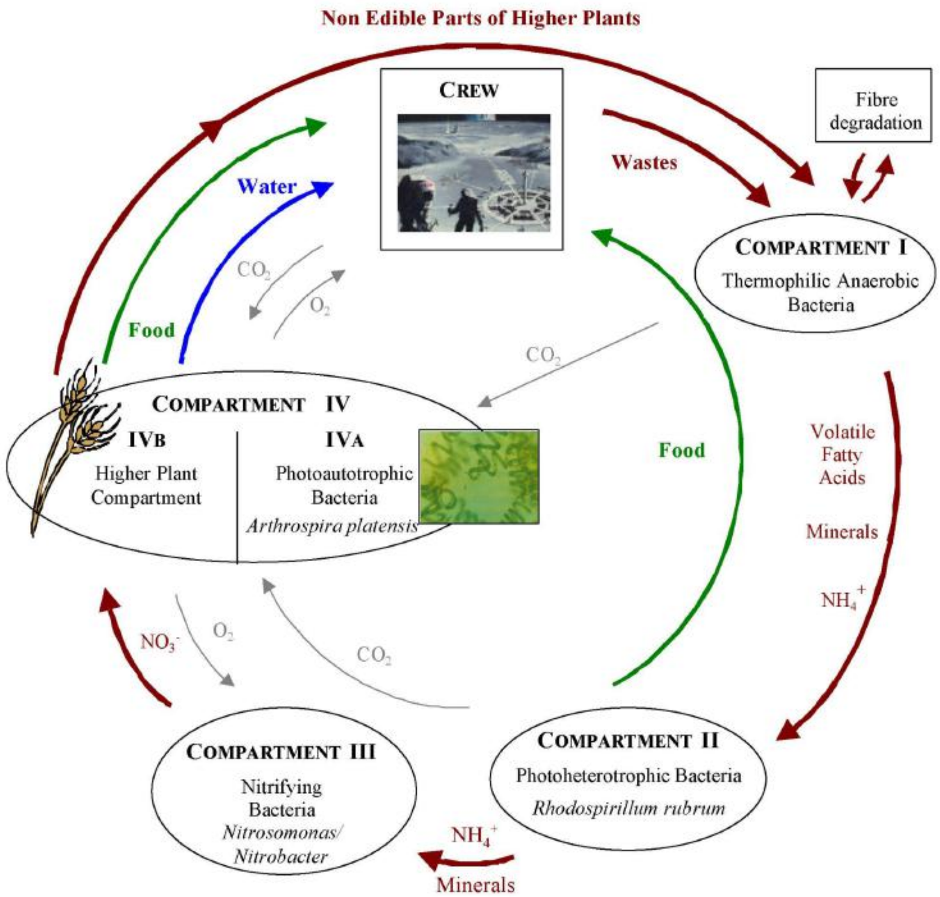

Figure 1: An example of a closed loop system, Source: MELiSSA's loop Diagram

A key consideration in addressing the challenge of sustaining humans on the Moon indefinitely is closed loops. The above diagram, produced by the ESA's Micro-Ecological Life Support System Alternative team (MELiSSA) provides an example of a closed-loop system. The recycling of resources or 'closed loop approach' of reusing resources is inspired by Earth's closed-loop systems, in which air and water are reused in cycles. Exploring the development of a closed loop system on the Moon would allow the reuse of otherwise rare elements on the Moon, such as carbon and nitrogen which are essential to food and life on Earth.

One example of a closed loop system was in 1989 when Linda Leigh spent 3 weeks in a small 400 sq ft (37 m^2) sealed test module, a precursor to Biosphere 2 (Nelson et al.). Inside the module was a scaled down complete life system from food production, to waste treatment. Linda Leigh says *"In such a closed environment, you can't help but be aware of every breath you take, every drink of water you consume, and every morsel of food you eat because it doesn't go someplace where you never* *see it again, it comes right back to you."* In space, if we stay, it also goes to the next generation rather directly. By closing the loop of resources, we bind the use and reuse within a single generation of humans. If toxic chemicals accumulate, they become a more immediate problem. Even if not immediately addressable, working knowledge of these gaps can prove valuable for future efforts both in space and on Earth.

At present a completely sealed system is impossible in space, there are slight leakages of gasses that contain carbon and nitrogen. With low availability of these two life essential elements on the Moon, carbon and nitrogen are particularly precious. Good stewardship and high rates of reuse within a closed loop system present a unique but increasingly relevant challenge to life on Earth as well.

A case for *Payload(Bay)X* is put forward in this paper, rather than a particular piece of hardware or puzzle piece to advance within a system, Payload(Bay) X could act as a board for the puzzle pieces to be integrated into. This concept draws inspiration from the International Space Station (ISS). Orbital Replacement Units (ORUs) are stowed on the ISS on external stowage platforms.

Current State of Life Support Technologies

This research focused on the resources for a sustained human presence on the Moon particularly within food, air, and water. A key consideration was how the associated important carbon and nitrogen flows could be improved to be utilized towards a more complete closed-loop system. A review of current technologies and the state of the art was conducted within the life support systems needed to live on the Moon. This paper explores the significant developments and current challenges associated with space life support systems.

Food Findings

Recent investments in food technology are yielding promising results in the form of continuous, minimally processed, high-protein food products. These innovations are on track for wide commercial use, as exemplified by companies like The Better Meat Co(Watson). In parallel, companies such as Solar Foods are developing cell-based protein products with specific applications in space exploration in mind ("Space"). One such product, Solein, is produced using hydrogen-oxidizing bacteria (HOB), also known as Knallgas bacteria. These single-celled organisms utilize hydrogen, carbon dioxide, and nitrogen to create protein.

While bioreactors for food production share similarities with common industrial processes like beverage fermentation, it's important to note that such systems are not without risks. Fermentation tanks used in alcohol production, for instance, are generally not considered hazardous, but serious accidents and explosions can occur (Lasbury). This underscores the need for careful consideration of safety measures in any bioreactor system, especially in the context of space applications.

Interestingly, there are overlaps between the hardware required for these advanced food production methods and other space-related technologies. For example, both supercritical water oxidation (SCWO) systems and advanced cellular food production require reactors that must withstand high pressures and ensure proper containment. In laboratory settings, equivalents to fume hoods can be implemented to manage at-risk activities and enable the safe operation of bioreactors in space. However, it's imperative to recognize that bioreactor operations come with physical, chemical, and biological hazards that must be carefully managed (*Chapter 14 Bioreactors*).

Given these considerations, there is a need to scale and test existing cell-based food production methods in sealed environments. This testing is important for identifying early accumulations of waste products in both air and water, which are of particular concern in a closed-loop system like a space habitat. As these systems become more relevant in terms of volume and power requirements, operating in a sealed, zero-waste environment becomes a challenge — one that is not typically a constraint in commercial settings on Earth.

To address these challenges effectively, it's essential to begin identifying gaps in our current approaches and integrating solutions into these novel food production systems. This can be achieved by conducting sealed condition testing, which will help determine which processes or scales are most applicable, and what the specific requirements and risks of these systems are.

Importantly, food production systems can be best tested and implemented if they are initially separated from human habitation requirements. This approach allows for more rigorous testing and refinement of the systems without putting human occupants at risk. As these technologies mature, they can then be gradually integrated into broader life support systems for space habitation.

Air Findings

Lunar missions require careful management of oxygen resources, both for crew respiration and to replace cryogenic fuel losses. The choice between open-loop and closed-loop air revitalization systems presents challenges. Closed-loop systems, which scrub CO_2 and reuse O_2, are currently mass-prohibitive for initial lunar missions, requiring ~2-5 metric tons initially and approximately 1 metric ton of annual maintenance materials for a 2-3 person crew. (*Harper et al. 2014*).

Despite the theoretical advantages of closed-loop systems, there's a movement back towards open-loop systems. This shift is driven by lower launch costs and concerns about hardware failure and maintenance in the harsh lunar environment. However, research into improving closed-loop systems continues. There are several ongoing projects focused on enhancing the Sabatier-based process, which is currently used in some space applications. Additionally, there's significant interest in an alternative approach centered around the Bosch process. The Bosch process holds a theoretical advantage over the Sabatier process in terms of oxygen recovery. While the Sabatier process has inherent limits on maximum O_2 recovery, the Bosch process can theoretically recover all of the O_2 trapped in metabolic CO_2, producing only solid carbon as a byproduct. The carbon generated during the process poses substantial issues, including clogging, contamination, and catalyst degradation.

These problems have made the Bosch process currently unfeasible for flight applications (Oliver-Butler and Stewart). It's worth noting that the elemental carbon produced by the Bosch process cannot be directly used to produce food through any known process. This limitation further complicates the potential utility of the Bosch process in space applications. From a resource utilization perspective, maintaining CO_2 in its gaseous form is preferred, as it can be more readily used in various life support and resource generation processes.

Water Findings

Water recovery from air and urine in space has achieved high-efficiency rates, with improved performance expected under lunar gravity conditions. However, solid waste processing in space remains a challenge, though ground-based testing for space applications is advancing.

Nitrogen recovery is of particular importance for lunar missions. As nitrogen cannot be sourced locally from the lunar surface, its efficient recovery and reuse are essential for extending human presence on the Moon. The scarcity of nitrogen in the lunar environment makes it a critical element that must be carefully managed and recycled.

The processing of solid faecal waste presents both opportunities and challenges. While it could potentially provide valuable resources, it currently faces significant barriers to implementation in space. These include additional health and safety hazards associated with handling solid faecal waste in a confined space environment. It's worth noting that nitrogen gas can also be recovered from urine through typical wastewater treatment processes, which may present fewer operational and safety concerns. Given these factors, prioritizing the development of urine treatment methods for nitrogen recovery could be a more practical approach to accelerate the reuse of this vital element.

Addressing trace contaminants in the wastewater stream is another critical aspect of waste management in space. Supercritical water oxidation (SCWO) is an innovative method being explored for this purpose. SCWO has proven effective in terrestrial applications for treating "forever chemicals" - persistent compounds that accumulate in wastewater streams - as well as biomedical waste. This technology holds promise for space applications due to its ability to treat a wide range of persistent organic chemicals, potentially preventing toxic accumulation in closed systems while also recovering elemental carbon and nitrogen. An additional benefit of SCWO is its capability to sterilize wastewater and materials, which is crucial for maintaining a healthy environment in space habitats.

Despite its potential benefits, SCWO has faced challenges in being adapted for space applications. The primary concern lies in its operational requirements, specifically the high temperatures and pressures needed for the process. These extreme conditions have historically been viewed as a safety risk in the context of space missions.

As we continue to develop technologies for sustained lunar presence, advancing these waste management and resource recovery systems will be crucial. Particular focus should be given to technologies that offer high efficiency in resource recovery while minimizing operational and safety risks. By doing so, we can significantly enhance resource utilization and sustainability for extended lunar missions, paving the way for long-term human presence on the Moon.

The Payload(Bay) X Concept

The integration of life support systems within lunar habitation units presents significant technical challenges. Safety concerns arise when operating these systems in sealed environments with human presence, leading to complex design requirements for co-located systems. These constraints result in limited operational flexibility, increased development costs, and restricted testing capabilities. Current approaches often require compromises between system efficiency and human safety, ultimately limiting our ability to implement innovative solutions for long-term lunar presence.

We propose an external modular platform system, designated Payload(Bay) X, that separates critical life support and processing systems from human habitation areas.

The core infrastructure consists of a standardized platform approximately 1m × 1.5m in size, designed to support 12U size hardware modules (20cm × 20cm × 34cm). The platform incorporates integrated power distribution, data communication networks, and fluid and gas distribution lines. These systems connect directly to habitation modules through standardized interfaces, enabling efficient resource transfer while maintaining operational independence.

Environmental protection represents a crucial design element of Payload(Bay) X. Light-duty hardware enclosures protect against lunar dust infiltration, while specialized shielding guards against UV radiation and atomic oxygen degradation. The system's thermal management capabilities allow operation across the extreme temperature ranges experienced on the lunar surface.

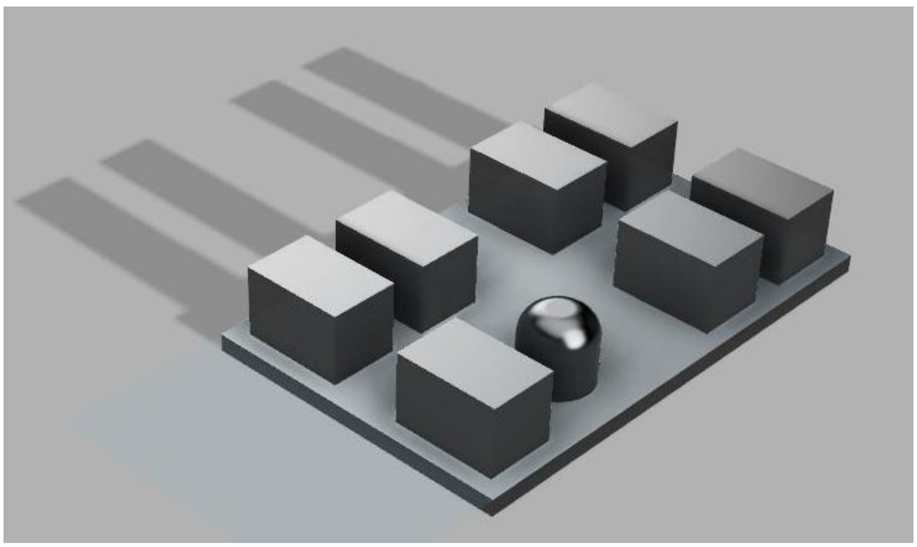

Figure 2: High-level potential concept of operation for Payload(bay) X

This modular design draws inspiration from the ISS' Orbital Replacement Units or (on-orbit replaceable units), see the figure below. Units can be exchanged with upgraded hardware and direct hardware failures would be limited to outside of habitation.

For spacecraft, a parallel can be made with service modules, which are located outside of crew cabins enabling to some extent crew safety during the accident with Apollo 13. Had the tank explosion occurred within the crew cabin vs. in the service module loss of crew would have been likely.

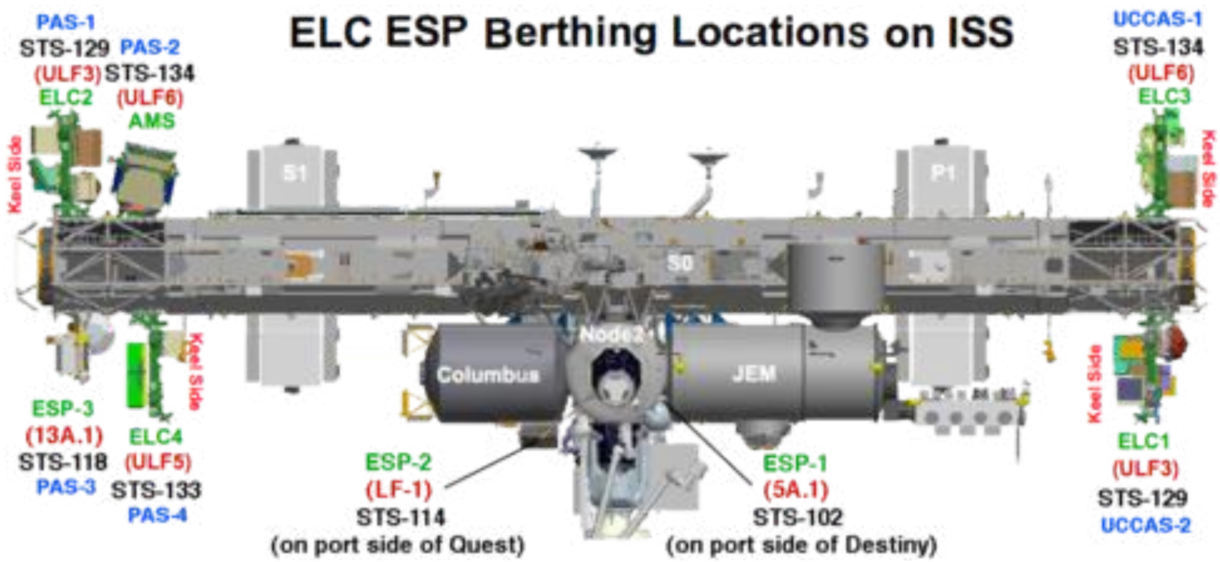

Figure 3: Orbital replacement units on the ISS

The figure above demonstrates one example of life support systems being separated from habitation. 29 of the ORUs relate to environmental control and life support systems, these are externally mounted systems with pumps, storage tanks, control boxes, and batteries, all of which are separate from habitation. The ISS presents one design approach for developing settlements on the Moon.

Payload(Bay) X Potential Benefits

The processes required for life support such as waste processing and food production can occur or be optimized for conditions that are not conducive to human life. These include a wider temperature profile, atmospheric composition and trace gas contamination. By removing these processes from the direct human loop, a wider range of operational conditions and risks can be utilized and avoided such as those not typically thought of with bioreactors as shown in brewery example above. Other potential benefits could include:

Operational Advantage

Thermal Environment Optimization

The lunar surface experiences extreme temperature variations, from +121°C during daylight to -133°C during nightfall. Payload(Bay) X aims to leverage these natural thermal gradients through strategic process placement. The proposed system could enable efficient CO_2 condensation in low-temperature zones while supporting Supercritical Water Oxidation (SCWO) processes in high-temperature areas. This deliberate zonation could create dedicated areas for temperature-sensitive operations, maximizing the natural thermal environment of the lunar surface.

Manufacturing Capabilities

The modular design of Payload(Bay) X could fundamentally transform manufacturing possibilities on the lunar surface. The proposed system could support autonomous 3D metal printing facilities operating at temperatures up to 1200°C, safely separated from human habitation areas. This separation could enable in-situ manufacturing of replacement parts, substantially reducing dependency on Earth-based supply chains. The resulting localized production capability could significantly lower overall mission costs through decreased transportation requirements and increased operational autonomy.

Cost Reduction Benefits

The proposed separation of critical processes from habitation zones could yield substantial cost savings throughout the system. Hardware development costs could decrease dramatically due to simplified safety requirements and the elimination of microgravity-compatible design constraints. This optimization could potentially reduce hardware costs from 50,000 USD/kg to 5,000 USD/kg. The simplified design architecture could enhance component serviceability and reproducibility, creating a more sustainable operational model for long-term lunar presence.

Experimental Capabilities

Payload(Bay) X serves as a dedicated platform for scientific research, providing isolated environments for specialized experiments. The system allows for detailed studies of extreme environment effects without risking crew safety. Multiple experimental units can operate concurrently, each maintaining specific environmental conditions required for different research objectives. The physical separation from habitation areas reduces the complexity and cost of safety mechanisms typically required for hazardous research.

Life Support System Development

The platform advances critical life support technologies through comprehensive testing opportunities. Engineers can evaluate closed-loop systems, physicochemical processes, and biological treatment methods in real lunar conditions. The integration of waste management solutions becomes more practical through dedicated processing zones. This approach allows for iterative development and refinement of life support technologies crucial for sustained lunar presence.

International Collaboration Benefits

Enhanced Cooperation

Payload(Bay) X could reduce technical barriers to international participation through its modular architecture. System integration could become more straightforward with standardized interfaces, enabling a "plug and play" approach to operations. This standardization could facilitate resource sharing and operational coordination between different lunar installations, fostering genuine international cooperation in lunar development.

Resource Management

The proposed system could enable sophisticated resource management through mobile transfer capabilities and long-term storage solutions. Waste products could become valuable resources, stored and processed for future use. Dehydrated carbon reserves, such as algal powder, could be maintained for extended periods. This approach could support multi-generational resource utilization planning, essential for sustainable lunar operations.

Conclusion

Current near-term plans for returning to the Moon are limited to short-duration missions similar to those conducted over 50 years ago, lasting approximately one week. These missions focus on scientific exploration and technology demonstrations, but do not yet address the requirements for longer-term, permanent human presence on the lunar surface.

The key challenges for sustaining a long-term human presence on the Moon include resource management, such as water requirements and water reuse, efficient food storage and production, and waste management strategies to address mass and volume constraints. Life support system challenges also arise, with physicochemical systems facing issues of contamination and chemical fouling, particularly of catalysts, while biological systems are susceptible to biofouling and biofilm formation, but offer potential for self-renewal and easier maintenance. Maintenance considerations differ, with biological systems more akin to aquarium maintenance and physicochemical systems potentially requiring in-situ manufacturing of replacement parts.

To address these challenges, a comprehensive baseline assessment and gap analysis of life support systems is crucial. This should cover the entire spectrum of challenges, from air revitalization to synthetic food production, with a particular focus on chemical accumulation in closed systems.

To shorten the timeline for sustainable human presence on the Moon, effectively managing the precious resources we bring will be essential. Imperfect hardware exists, particularly when considering operations at a small scale, in a small sealed environment, and maintaining low-risk conditions for human life. By removing humans from the direct life support loop, we can lower the hardware development cost and not change existing spacecraft and habitation systems, while beginning and accelerating the reuse of resources with multi-generational intent.

Drawing inspiration from the modular design of the International Space Station's Orbital Replacement Units (ORUs), the concept of "Payload(bay) X" has been proposed. This approach applies the modular design to an operational platform on the lunar surface. This could potentially accelerate the implementation timeline for a number of life support systems by removing the various requirements associated with co-locating certain processes with humans. Additionally, a modular design could allow for a greater level of experimentation to take place, again without fear of risk to humans.

Next steps for Payload(bay) X could include conducting studies on high-level mass flows required to sustain a long-term human presence on the Moon, identifying simple external system types that could be attempted to extend durations on the Moon using available existing Earth hardware, exploring how these external systems could be configured to create a closed-loop life support system, separate from but connected to the lunar habitats, and investigating how in-situ resource extraction, refinement, and manufacturing can be integrated into the external platform to further extend a permanent human presence on the Moon.

By addressing the key challenges of resource management and life support systems through innovative approaches like Payload(bay) X, the path towards enabling a sustainable, long-term human presence on the lunar surface can be accelerated.

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