# SPACE RESOURCE UTILIZATION CONSIDERATIONS FOR A LUNAR HABITATION CUSTOMER

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**Introduction:** Both the National Aeronautics and Space Administration (NASA) Artemis missions and the Chinese-Russian International Lunar Research Station (ILRS) campaign identify a series of mission segments that promise increasing human presence and space resource utilization (SRU) activities [1,2]. While a primary SRU business case has been propellant production, habitation Environmental Control and Life Support Systems (ECLSS) may also be a customer of in-situ produced oxygen ($O_2$) and water ($H_2O$). Despite the low consumable demands of near-term human missions, habitation customers may hold significant value in in-situ $O_2$ and $H_2O$, with a projected combined value of $20M USD or more per mission [3]. The prospect of small scale, high-value consumable production warrants a deeper understanding of habitation customer interfaces for those in the SRU community.

*Habitation ECLSS.* SRU developers must understand the needs of its prospective customers to build a successful business case. Habitation ECLSS supplies potable $H_2O$, food, $O_2$, and other atmospheric gases to crews in space in addition to processing, storing, and/or dumping waste streams and atmospheric contaminants. A critical design trade in designing habitation ECLSS is deciding between 'open-loop' systems which rely on consumable resupply or regenerative 'closed-loop' systems which recycle wastewater and gases. Open-loop systems carry the benefit of lower mass and less maintenance while closed-loop systems offer lower consumable needs but carry a penalty of higher mass and maintenance needs. The ability to acquire consumables for open-loop ECLSS through SRU methods instead of from Earth provides a synergistic opportunity for both communities if key considerations are made throughout system design.

**SRU Value Chain Considerations:** Extraction, processing, storage, and delivery are key steps in the SRU value chain which require consideration of a prospective habitation customer.

*Extraction Considerations.* The quantity of raw material that needs to be extracted for a habitation customer is based upon metabolic usage and habitation ECLSS design. Metabolic demand is calculated from validated models that simulate an 82 kg average male and is captured in Table 1 for three near-term mission sets as identified by Harris et al. [4,5]. Vehicle atmospheric leakage (estimated at 0.02 kg/day/module), gas losses from airlock depressurization, and payload and spacesuit needs may all increase demand, thereby suggesting metabolic needs are the minimum [4].

*Table 1 Metabolic demand for representative mission sets.*

| Consumable | Metabolic demand per crewmember per day (CM-d) | 2 crew, 30-day mission total demand | 4 crew, 30-day mission total demand | 4 crew, 60-day mission total demand |
|---|---|---|---|---|
| Oxygen (kg) | 0.895 | 53.7 | 107.4 | 214.8 |
| Water (kg) | 3.217 | 193.0 | 386.0 | 772.0 |

These demands factor into extraction quantities based upon the SRU methodology used. With a series of generalized assumptions that include extracting water ice for crew potable $H_2O$ demand and regolith for $O_2$ needs (both with assumed 20% production losses), extraction quantities are expected to be significantly less than the 100s of tonnes of excavated material assumed for several propellant based SRU business cases (see Table 2).

*Table 2 Estimated excavation needs to meet metabolic demand.*

| | Assumed wt% of resource in regolith [6] | Habitation ECLSS Need, 4 crew, 60-days (kg) | Est. raw material to excavate w/20% production losses (kg) |
|---|---|---|---|
| Regolith-only ($O_2$) | 40% | 214.8 | 402.8 |
| Water ice-only ($H_2O$) | 5% | 772.0 | 18337.4 |

Further optimization can be made assuming a single resource and SRU processing methodology (e.g., water ice yielding both water as well as oxygen via electrolysis). This extraction demand suggests far smaller and simpler SRU pilot systems are needed for early human missions, likely reducing investment costs and risks for proving SRU capabilities to technology readiness level 7+.

*Processing Considerations.* Processing may provide the greatest challenge for SRU systems with the need for high-purity $O_2$ and $H_2O$ fit for human consumption. In-situ produced $O_2$ and $H_2O$ would likely need to meet use specifications as identified in International Organization for Standardization (ISO) 15859 *Space Systems – Fluid Characteristics, Sampling, and Test Methods* Parts 1 (Oxygen) and 10 (Water). These specifications may differ from procurement specifications set by the end user, which may be more or less stringent [7]. Other guidance on overall breathing air composition may be referenced in Spacecraft Maximum Allowable Concentrations (SMAC) documentation. A comparison of $O_2$ procurement specifications for Space Shuttle breathing $O_2$ and gaseous $O_2$ for propellant usage suggests that breathing gas may have slightly less processing needs than propellant (see Table 3).

*Table 1 Comparison of Oxygen procurement specifications [8].*

| | Breathing O2 | Propellant O2 |
|---|---|---|
| Purity by vol. (min.) | 99.500% | 99.989% |
| Moisture | 10 ppm | 3 ppm |
| Total hydrocarbons as CH4 | 50 ppm | 23 ppm |
| Alkynes | -- | 0.05 ppm |
| Nitrous oxide | 4 ppm | 1 ppm |
| Halogenated hydrocarbon | 2 ppm | 1 ppm |
| Chlorinated hydrocarbons | 0.2 ppm | 0.1 ppm |
| CO2 | 10 ppm | 1 ppm (combined) |
| CO | 10 ppm | |

Potable $H_2O$ quality specifications include both chemical and biological compounds with exposure limits tied to mission duration. These specifications also point to additional standards and guidance, such as the Environmental Protection Agency National Primary Drinking Water Regulations and NASA's Spacecraft Water Exposure Guidelines (SWEGs). Several volatiles identified in NASA's SWEGs and in a specification for Water Processor Assembly (WPA) system product water were also observed in the Lunar Crater Observation and Sensing Satellite (LCROSS) impact plume which liberated water from Cabeus crater. While lunar water quality specifications have yet to be developed, current maximum concentration limits (MCLs) may provide an initial baseline for in-situ extracted water (see Table 4) [9-11].

*Table 3 Water specification comparison for applicable LCROSS plume volatiles.*

| | $NH_3$ | $CH_3OH$ | $CO_2$ |
|---|---|---|---|
| **Concentration (% by weight) in LCROSS Plume** | 0.32% | 0.15% | 0.29% |
| **WPA Potable $H_2O$ Specifications** | 0.5 mg/L | N/A | 15 mg/L |
| **SWEG MCL (100-days)** | 1 mg/L | 40 mg/L | 15 mg/L |

*Storage & Delivery Considerations.* Storage of in-situ produced consumables for habitation ECLSS is expected to be simpler than for propellant due to smaller quantities and no need for cryogenic storage. While no lunar storage systems for ECLSS have been developed, solutions aboard the ISS may be leveraged with appropriate modification such as Nitrogen/Oxygen Recharge System (NORS) tanks and Russian ЕдV water containers. These systems hold ~33 kg of $O_2$ and ~22 kg of $H_2O$ respectively, are designed for crew transport, and in the case of NORS tanks, are already designed for use in the vacuum of space. Modified versions of such heritage systems will likely support initial consumable resupply from Earth and will be discarded on the lunar surface when expended, creating an opportunity for their repurposing by the SRU community.

Complimentary to storage considerations are those of delivery. Assuming in-situ resource excavation and processing operations will be physically separated from a habitation customer, some level of mobility will be needed to deliver consumables for use. While no requirements currently exist for the separation of SRU extraction and processing from a habitation customer, Kleinhenz and Paz suggested a traverse distance of ~5.2 km (inclusive of margin for route-finding) between excavation and processing locations [12]. Using similar margins, an additional distance of ~6.2 km may be inferred from Kleinhenz and Paz between a processing location and a notional habitation site. Where possible, co-location of processing equipment to a habitation customer would reduce the operational complexity and the energetic cost of transporting consumables.

**Conclusion & Forward Work:** In reviewing the key considerations for a SRU habitation customer, we note that the smaller demand results in simpler extraction and storage needs. Further work is needed in identifying SRU product delivery specifications, although some standards do currently exist outside of a SRU context and can be leveraged as a starting point. The combination of reduced demand and simpler systems may be attractive for small-scale SRU concepts to prove technological feasibility with a beta customer.

**References:**

[1] NASA. (2022). *NASA's Deep Space Exploration Plans*. National Aeronautics and Space Administration (NASA). [2] China National Space Administration (CNSA). (2021, June 16). *International Lunar Research Station (ILRS) Guide for Partnership.* Retrieved at: http://www.cnsa.gov.cn/ [3] Johnson, James E. (2024, March 25-27). *Small Steps to Giant Leaps: Habitation as a Near-Term Lunar Resource Use Case.* [Poster Presentation]. Space Resources Week 2024, Luxembourg. [4] Ewert, M. K., Chen, T. T., & Powell, C. D. (2022). *Life Support Baseline Values and Assumptions Document* (Technical Paper NASA/TP-2015–218570/REV2; p. 235). National Aeronautics and Space Administration. [5] Harris, D. W., Kessler, P. D., Nickens, T. M., Choate, A. J., Horvath, B. L., Simon, M. A., & Stromgren, C. (2022). *Moon to Mars (M2M) Habitation Considerations* (Technical Memo NASA/TM-20220000524; NASA STI Program Report Series). National Aeronautics and Space Administration (NASA). [6] Badescu, V., Zacny, K., & Bar-Cohen, Y. (Eds.). (2023). *Handbook of Space Resources*. Springer International Publishing. [7] Greene, B., McClure, M. B., & Baker, D. L. (2006, March 6). ISO 15859 PROPELLANT AND FLUID SPECIFICATIONS: A REVIEW AND COMPARISON WITH MILITARY AND NASA SPECIFICATIONS. *22nd SEPS Joint Meeting*. [8] Schlüter, L., Cowley, A., Pennec, Y., & Roux, M. (2021). Gas purification for oxygen extraction from lunar regolith. *Acta Astronautica*, *179*, 371–381. [9] Ennico-Smith, K. (2023). Lunar Crater Observation and Sensing Satellite (LCROSS). In: Cudnik, B. (eds) Encyclopedia of Lunar Science. Springer, Cham. [10] Carter, L., Tabb, D., Tatara, J. D., & Mason, R. K. (2005, July 11). Performance Qualification Test of the ISS Water Processor Assembly (WPA) Expendables. *34th International Conference on Environmental Systems*. ICES, Rome, Italy. [11] NASA. (2023). *Spacecraft Water Exposure Guidelines* (JSC 63414; Rev A). Johnson Space Center. [12] Kleinhenz, J. E., & Paz, A. (2020, November 16). Case Studies for Lunar ISRU Systems Utilizing Polar Water. *ASCEND 2020*, Virtual Event.