Lunar Surface Innovation Consortium

JOHNS HOPKINS APPLIED PHYSICS LABORATORY

Oxygen from Regolith (O2fR) Collaborative Systems Interface Study: Implications for Lunar Infrastructure

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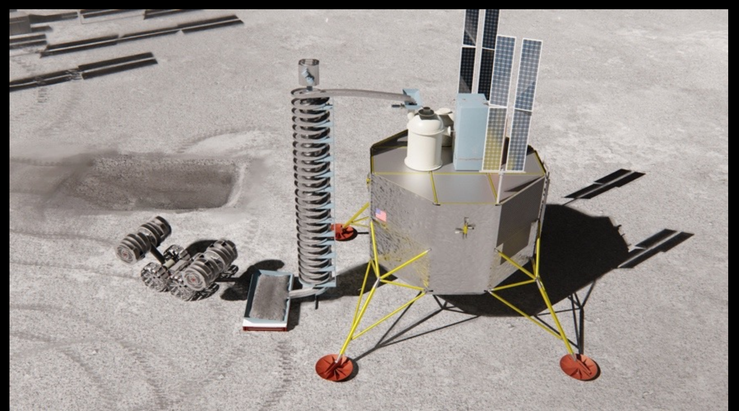
Importance of ISRU Interfaces

Starting in 2024, the team analyzed interface needs for an Oxygen from Regolith (O2fR) CONOPS, including community inputs gathered through a series of workshops and roundtable discussions from lunar ISRU subject matter experts and stakeholders. To further define the needs, functions, constraints, and requirements before testing, integrating, and operating a pilot plant, the study found that a rigorous systems engineering approach is needed. Specifically, a system-of-systems perspective is key to coordinating the interdependent subsystems of a pilot plant that collectively support end-to-end autonomous ISRU operations. For any given function in the CONOPS, there are multiple options for the technology-specific hardware that performs them. Each technology option presents different interface conditions that must be well understood and tested to become interoperable with the system and maintain the oxygen throughput of the plant. Proactive interface management is essential for matching throughput across subsystems, ensuring system interoperability, and minimizing redesign – enabling the pilot plant to reliably achieve its oxygen production goals. This study developed methods to enable identification and detailed analyses of key ISRU interfaces.



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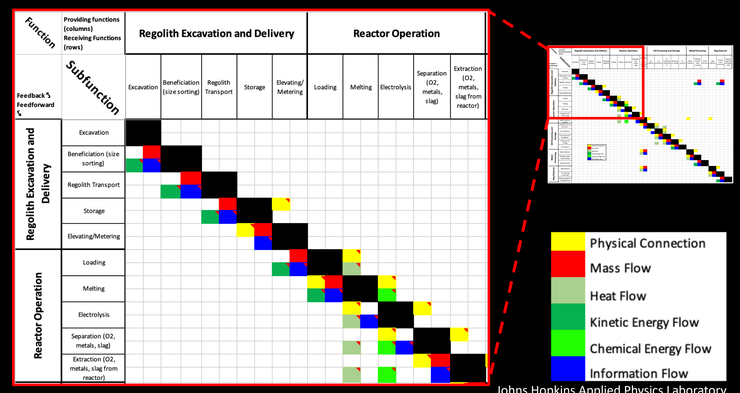
Design Structure Matrix (DSM)



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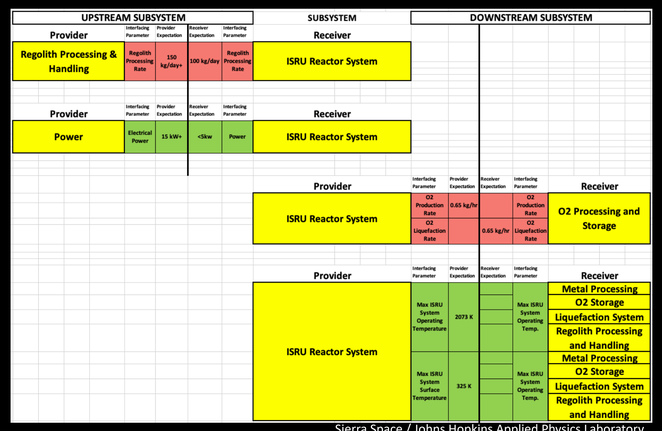
The design structure matrix is an at-a-glance view of the functional interactions of an ISRU system. The goal of this matrix is to highlight functional dependencies between the system of interest and the rest of the ISRU functions. The identical functions and subfunction columns and rows are taken from a functional decomposition of a lunar oxygen from regolith system. At any intersection between two unique subfunctions is a 2x2 matrix. If a functional interaction occurs between those two subfunctions, the cells are highlighted to the corresponding field.

O2fR Product Development

All products from the O2fR study are publicly available to the LSIC community on the **O2fR Interface Database** Wiki page (see O2fR Database Section and QR code). Outputs from our study include:

- 2 Excel systems engineering templates:
  - **Interface worksheet** to track a given technology's inputs and outputs across interfaces as well as that technology's expectations for inputs/outputs of adjacent subsystems.
  - A **design structure matrix (DSM)** to serve as an at-a-glance decomposition of an ISRU system, with highlights to indicate functional dependencies between subsystems.
- **Community-completed worksheets** to provide a glimpse into the community's actual ISRU subsystem interfaces ahead of integration, including regolith processing rates, operating temperatures, slag production rates, power needs, and more.
- **Integrated data worksheet** that gathers the information of all community-completed worksheets in one place and in a sortable format.
- **ReadMe document** to complete your own O2fR workbook.
- 2024 and 2025 LSIC ISRU workshop recordings focusing on the O2fR study applied to the ISRU community's systems.

Interface Worksheet



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The Interface Worksheet was developed to provide a detailed look at the interface parameters each subsystem needs to work smoothly with others.

Upstream and Downstream Subsystems: Columns separating the upstream subsystem (left), downstream subsystem (right), and the workbook author's subsystem (center).

Interfacing Parameters: Mass, energy, or operational demands that require collaboration between a pair of interfacing subsystems.

Parameter Values:

- Upstream Subsystem Provider Capability: Quantifies the parameter values a subsystem can deliver at an interface—well understood internally but often not fully visible to downstream partners.
- Downstream Subsystem Receiver Expectation: Defines the expected range of incoming parameter values at an interface, which must align with upstream capabilities.

Integrated Data Worksheet

	A	B	C	D	E	F	G	H
1	Upstream Interface	Downstream Interface	Interface Parameter	Upstream Parameter Value	Downstream Parameter Value	Material	Parameter Units	Organization
2	O2 Storage	Life Support System	Metabolic Demand		0.833333333	O2 (gaseous)	kg / crew-day	Colorado School of Mines
3	O2 Storage	Life Support System	Other Habitation Demand		0.608333333	O2 (gaseous)	kg / crew-day	Colorado School of Mines
4	O2 Storage	Life Support System	Temporary Storage Tanks		5		high-pressure gas canisters O2 tanks / mission	Colorado School of Mines
5	Regolith Processing and Handling	Reactor	Regolith Processing Rate	6536	168	Lunar Regolith	kg / day	White Paper
6	Power	Reactor	Power	30	20	Power	kW	White Paper
7	Reactor	O2 Processing & Storage	O2 Production Rate	10,000		O2	kg / year	White Paper
8	Reactor	Metal Processing	Iron Processing Rate					White Paper
9	Reactor	Metal Processing	Ferro-Silicon Processing Rate					White Paper
10	Reactor	Metal Processing	Maximum Reactor Operating Temperature	2073			K	White Paper
11	Reactor	O2 Storage	Maximum Reactor Operating Temperature	2073			K	White Paper
12	Reactor	Liquefaction System	Maximum Reactor Operating Temperature	2073			K	White Paper
13	Reactor	Regolith Processing and Handling	Maximum Reactor Operating Temperature	2073			K	White Paper

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The Integrated Data Worksheet contains an accumulation of all community input received thus far, including all relevant information from each completed Interface Worksheet (upstream/downstream parameter, parameter value, upstream/downstream interface, etc.). This enables an interactive and accessible user interface, including the ability to sort/choose specific interfaces, threshold on parameter values, and trace each dataset to a particular institution.

Motivation of the O2fR Study

Just like our community, the LSIC ISRU Capability Area (CA) is interested in advancing the discussion of the systems engineering **gaps, needs, and solutions for Oxygen from Regolith systems.**

- Our worldwide community of technologists spans industry, academia, government, and non-profit organizations. These members are developing the ISRU subsystems needed to extract resources from the lunar surface, including oxygen, metals, and more, to enable our permanent presence on the Moon. **A diverse set of individual ISRU elements must interface, integrate, and function together to achieve our collective goal of sustainable lunar ISRU plant operations that support the Moon Base.**
- The LSIC ISRU CA conducted the O2fR study to encourage community members to think about their technology from a system-level perspective. To further this goal, we developed Excel-based templates to help technology developers better understand how their elements fit into the system and to proactively track ISRU system-level information.
- These templates serve as a common language for the LSIC ISRU community to assess parameters at subsystem interfaces as well as functional dependencies between subsystems. By surveying the community's interface designs, capabilities, and expectations early, we can check for system compatibility well ahead of ISRU integration and test campaigns.
  - The templates presented extend beyond O2fR plants and can be applied to any other lunar system-of-systems.

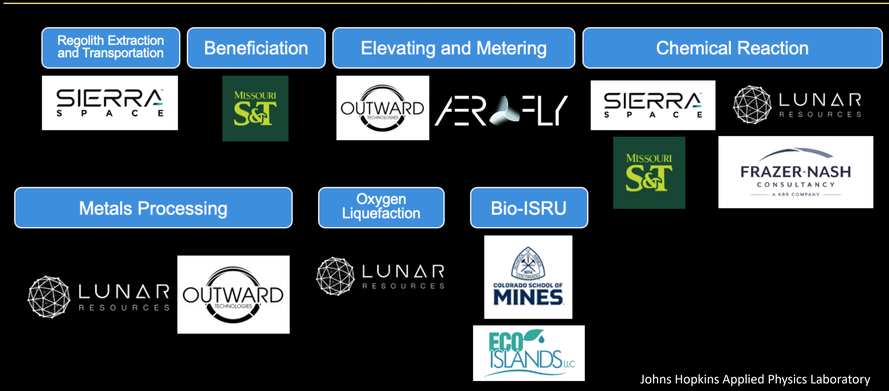
O2fR Database

The Oxygen from Regolith (O2fR) Collaborative Systems Interface Database is maintained on the LSIC ISRU Confluence page. The database includes the O2fR Collaborative Systems Interface Workbook template, ReadMe, O2fR Workbooks completed by organizations, and the Integrated Data Worksheet. By publishing on Confluence, any ISRU community member that has an LSIC Confluence account can easily access the data which can be updated as projects evolve.

To access Confluence, sign up as an LSIC participant by visiting https://lsic.jhuapl.edu/News/Sign-Up.php and then request an LSIC Confluence account by emailing ses-lsic-wiki-admins@jhuapl.edu

O2fR Database Confluence Page

Community Participants



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Study Findings and Recommendations for Lunar Infrastructure

The O2fR Collaborative Systems Interface effort showed that lunar ISRU success depends as much on well-defined subsystem interfaces as on the individual extraction technologies themselves. Understanding and tracking interfaces, as described in the poster, will help teams identify and communicate interdependencies early in design. For lunar infrastructure planning, O2-from-regolith should be treated as a system-of-systems integration challenge, not only a reactor-development problem. Excavation, beneficiation, transport, reactor feeding, oxygen processing, storage, metals/slag handling, and supporting logistics must be coordinated through explicit interface definitions so that throughput, timing, and product quality remain aligned across the full architecture.

- **Interface standards emerged as the strongest community need**. For lunar infrastructure compatibility, standards on regolith feed characteristics, oxygen product specifications, contamination limits, power interfaces, communications, and synchronized operations should be established early.
- **Design infrastructure around modular, interoperable building blocks** so pilot plants can scale through aggregation, staged deployment, and subsystem replacement rather than complete redesign
- **Mission requirements and end-user needs remain underdefined**, limiting how well developers can size and optimize their systems for real lunar demand
- **Critical interface variables span the full plant architecture**, including regolith morphology and composition, feed rate, pressure, temperature, oxygen purity, contamination, throughput, and waste/byproduct handling
- **Use terrestrial testbeds and subsystem demonstrations to retire integration risk early**, especially for dust-tolerant connections, regolith flow, pressure boundaries, thermal management, and oxygen processing/storage interfaces

References

- 2024 LSIC Oxygen from Regolith Collaborative Systems Interface Workshop
- 2025 LSIC Testing, Interfacing, and Funding Workshop
- Space Resources Roundtable 2025: *Key Findings and Path Forward from the Oxygen from Regolith (O2fR) Collaborative Systems Interface Study*
- ASCEND 2025 Workshop: *Lessons Learned, Forward Path, and Collaboration from the Oxygen from Regolith (O2fR) Collaborative Systems Interface Workshop*
- ASCEND 2025 Technical Paper and Presentation: *Oxygen from Regolith (O2fR) Collaborative Systems Interface Study Path Forward*

Acknowledgements

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