Lunar Surface Innovation
CONSORTIUM

Johns Hopkins
Applied Physics Laboratory

In-Situ Resource Utilization (ISRU) Focus Group Update to Space Resources Roundtable

Drs. Charles A Hibbitts, Michael Nord, Kirby Runyon, Jodi Berdis, Dave Smith
June 7, 2022

LSIC ISRU Focus Group

Mission: Enabling the development of lunar surface ISRU technologies, specifically the extraction, storage, and utilization of O_2, H_2O, other volatile resources, as well as metals, and identifying the technologies most in need of support.

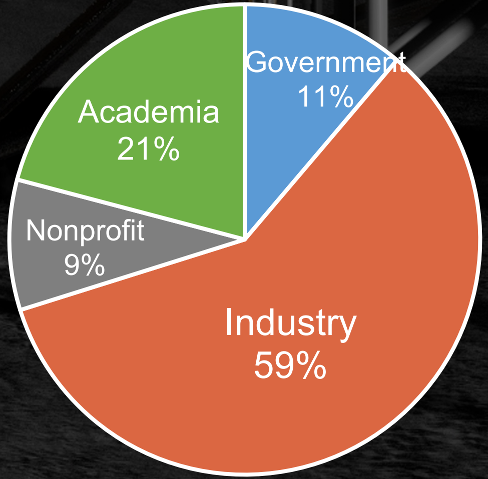
Current Foci: Value Networking; O_2/metal extraction; Water-ice Prospecting & Extraction; Maintenance, Interoperability, and Standards

Enable development of needed tech, from a system perspective.

Meetings: 3rd Wednesday of the Month 3:00 – 3:50 pm EST (+ another 40 min)

Mailing List: LSIC_ISRU@listserv.jhuapl.edu

Website: http://lsic.jhuapl.edu/Focus-Areas/ISRU.php



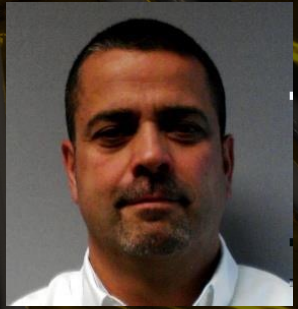
Applied Physics Laboratory

Karl Hibbitts

Michael Nord

Kirby Runyon

Jodi Berdis



Dave Smith

NASA

Jerry Sanders
ISRU Systems Capability Lead

Omar Hatamleh
ISRU Technical Integration Manager

Resources for the Community

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ISRU Library & Resources

Created by Andrea Harman, last modified about 2 hours ago

Links to Articles

- Analysis and prediction of uniaxial compressive strength of icy lunar regolith under extreme temperature https://www.sciencedirect.com/science/article/pii/S0273117722002502
- Predicting the efficiency of oxygen-evolving electrolysis on the Moon and Mars
  - https://www.nature.com/articles/s41467-022-28147-5
- Commercial lunar propellant architecture: A collaborative study of lunar propellant production https://www.sciencedirect.com/science/article/pii/S2352309318300099
- Concentrated lunar resources: imminent implications for governance and justice, Martin et al., 2021 https://royalsocietypublishing.org/doi/10.1098/rsta.2019.0563
- Framework for Coordinated Efforts in the Exploration of Volatiles in the South Polar Region of the Moon, Lemelin http://doi.org/10.3847/PSJ/abf3c5
- Helium-3 mining https://www.transparencymarketresearch.com/helium3-market.html
- In Situ Resource Utilization Gap Assessment Report https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-
- International Deep Space Interoperability Standards https://www.internationaldeepspacestandards.com/
- Logistics in Support of lunar bases (Woodcock, 1988) https://www.sciencedirect.com/science/article/abs/pii/0094576588901865
- Lunar and off Earth resource drivers, estimations and the development conundrum", Donald Barker, 2020 https://www.sciencedirect.com/science/article/pii/S0273117720302234?via%3Dihub
- Space Manufacturing 5 https://ssi.org/ssi-conference-abstracts/space-manufacturing-5/
- Towers on the Moon: 1. Concrete., Ruppert et al., 2021 https://arxiv.org/pdf/2103.00612.pdf
- Towers on the Peaks of Eternal Light: Quantifying the Available Solar Power, Ross et al., 2021 https://arxiv.org/abs/2102.11766
- NASA Space Resources (Energy, Power, Transport) Report, 1992 https://space.nss.org/settlement/nasa/spaceresvol2/toc.html
- NASA Standards for testing equipment in a dusty environment https://standards.nasa.gov/standard/nasa/nasa-std-1008

Books

- Vol. 1: "Advances in Terrestrial Drilling: Ground, Ice, and Underwater" https://www.amazon.com/Advances-Terrestrial-Drilling-Ground-Underwater/dp/036765346X
- Vol. 2: "Advances in Extraterrestrial Drilling: Ground, Ice, and Underwater" https://www.amazon.com/Advances-Extraterrestrial-Drilling-Ground-Underwater/dp/0367653478

Files

- Air Liquide Space Environments Test Capabilities - December 2020.pdf
- Case Studies for Lunar ISRU Systems Utilizing Polar Water.pdf
- Current NASA In Situ Resource Utilization (ISRU) Strategic Vision.pdf
- Hubble Space Telescope Servicing Lessons Learned
- Lunar Water ISRU Measurement Study (LWIMS).pdf
- Lunar Water Pilot Plant Conceptual Design.pdf
- Lunar Water Reference Case Study.pdf
- Lunar-G Quickstart Guide (Blue Origin)
- Moon to Mars Oxygen and Steel Technology (MMOST)
- Perspectives on the NASA ISRU Roadmap and the Lunar Science Innovation Consortium.pdf
- Planetary Protection for the Study of Lunar Volatiles (2020)
- Planetary Protection Perspectives for the Moon
- Propellant Standards
- ROXY: Regolith to Oxygen & Metal Conversion Lunar Demonstrator
- Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison.pdf
- Space Mining - Deltion Innovations.pptx
- STPI Cis Lunar Economy Report
- US-NRC document containing information on magma viscosity
- Who Wants To Buy And Sell On The Moon?
- https://www.lpi.usra.edu/publications/books/lunar_bases/LSBchapter03.pdf (Transportation Issues)
- https://www.kiss.caltech.edu/final_reports/Lunar_Ice_final_report.pdf (KISS study)
- https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-Assessment-Report-Apr-2021.pdf (2021 ISRU Assessment Report by the International Space Exploration Coordination Group)

Websites

- Small Satellite Reliability Initiative (SSRI) Best Practices

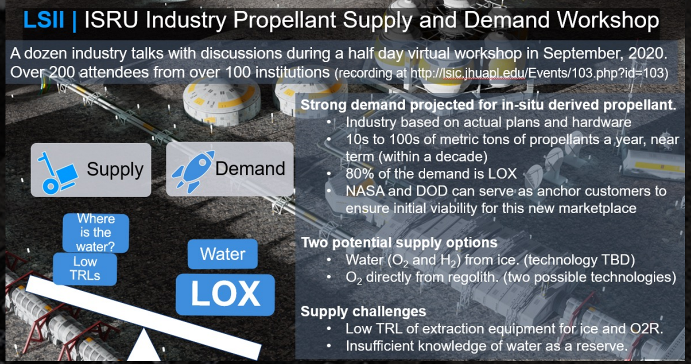
Communications with the Community

Monthly meetings

As well as monthly meetings by:
Surface Power
Excavation & Construction
Dust Mitigation
Extreme Access
Extreme Environments

Periodic large meetings and thematic workshops

Semi-annual LSIC meetings



Networking within the Community

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Who's Who in ISRU

Created by Kirby Runyon, last modified by Noah Singer 27 minutes ago

Make sure that you stay on the radar of *all* of NASA and the rest of the community! Fill out the table below for your institution; don't be shy! Please don't delete other entries. **Add new entries to the bottom.**

1-minute introductory videos from the June 16, 2021 networking focus group meeting are viewable here: https://lsic-wiki.jhuapl.edu/x/i5DL.

Other Focus Groups:

- Who's Who in DM
- Who's Who in EA
- Who's Who in EE
- Who's Who in E&C
- Who's Who in SP

Who You Are	What You Do	What You Want Others to Know about You	Other Comments
Example: Prospect for and mine Münster, Gouda, and other soft cheeses from mid-latitude Procellarum-KREEP terrain	Example: Happy to license Cheese Detection and Ranging (CheDAR) technology to NASA and commercial partners	Example: Working with STMD; looking to engage with SMD and Wisconsin dairy farmers	Do not delete this row. Please don't delete other er **Add new entries to the bc**
Sierra Space	Sierra Space is formerly part of Sierra Nevada Corporation (SNC). Sierra Space has a diverse technology portfolio, including the carbothermal reduction of lunar regolith to produce oxygen. Other business areas include the Dream Chaser flight vehicle, propulsion systems, life support, and on-orbit	Sierra Space is currently maturing the carbothermal reduction process to extract oxygen from lunar regolith. Sierra Space and SNC have been advancing this technology over the last ~25 years under NASA contract and internally. This work, in tandem with lunar materials handing research, is being used to develop an integrated oxygen production plant capable of producing 3.5 MT of oxygen per year on the Moon.	? Unknown Attachment

60 entries out of several hundred ISRU FG members

https://lsic-wiki.jhuapl.edu/

Part II: Value Networking

Defining Basic Requirements

LSII | ISRU Industry Propellant Supply and Demand Workshop

A dozen industry talks with discussions during a half day virtual workshop in September, 2020.
Over 200 attendees from over 100 institutions (recording at http://lsic.jhuapl.edu/Events/103.php?id=103)

Supply

Demand

Where is the water?

Low TRLs

Water

LOX

Strong demand projected for in-situ derived propellant.

- Industry based on actual plans and hardware
- 10s to 100s of metric tons of propellants a year, near term (within a decade)
- 80% of the demand is LOX
- NASA and DOD can serve as anchor customers to ensure initial viability for this new marketplace

Two potential supply options

- Water (O_2 and H_2) from ice. (technology TBD)
- O_2 directly from regolith. (two possible technologies)

Supply challenges

- Low TRL of extraction equipment for ice and O2R.
- Insufficient knowledge of water as a reserve.

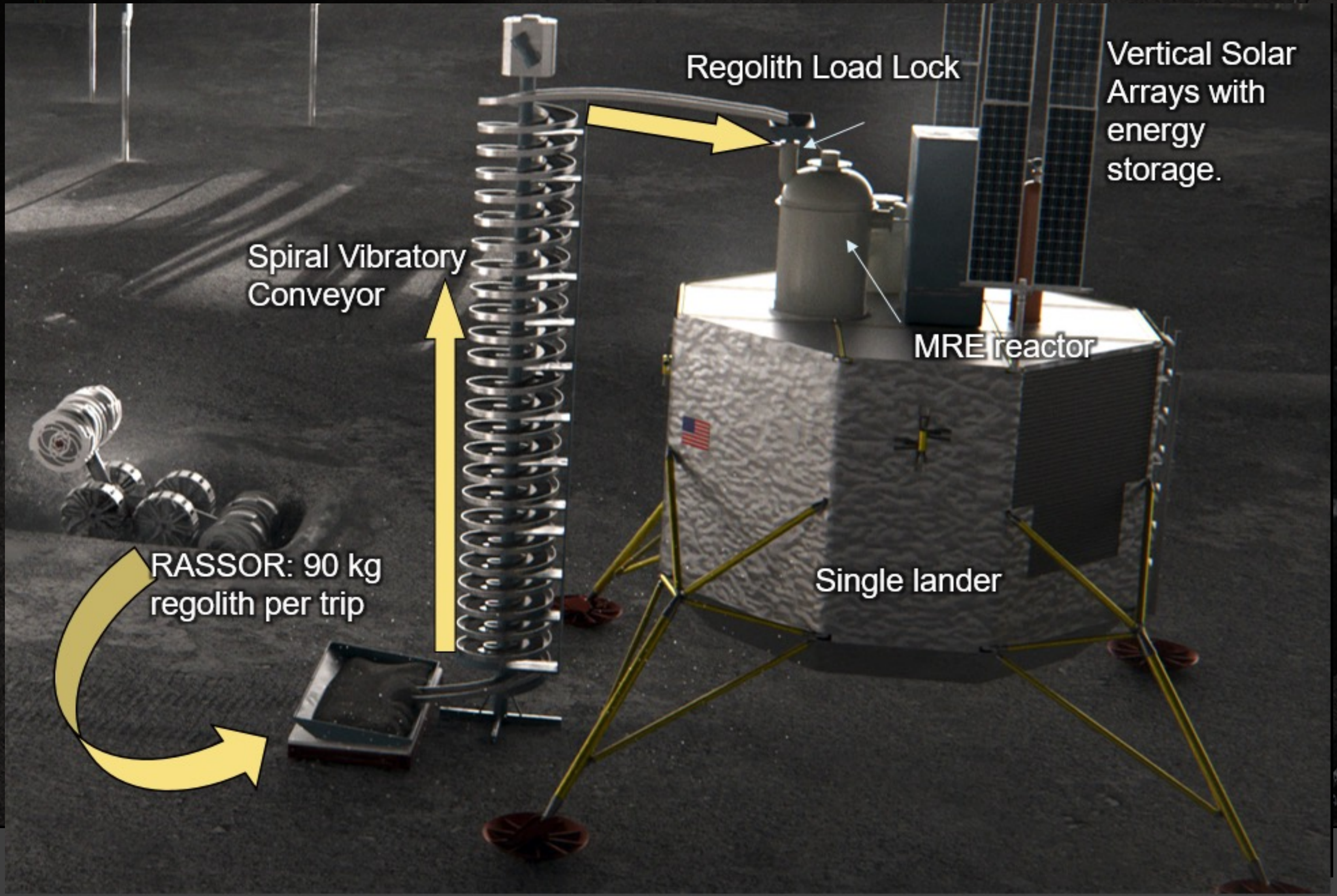
Do we need a follow-on?

Input to Surface Power

Led to recommendations to NASA.

System Study of Technology for O_2 Extraction

Help O_2/metal extraction technologies to be as successful as possible by identifying and helping find solutions to core challenges and by acting as lunar subject matter experts.



Key technologies:
H-reduction; Carbothermal Reduction; Vapor Pyrolysis, Molten Regolith Electrolysis, Molten Salt Electrolysis

Conclusion: Likely feasible; a demonstration of key technology needed.

Some core challenges:
System design including maintenance and interoperability.
Technical (for some technologies) such as melt viscosity and conductivity

LSIC | Lunar “Regolith to Rebar” Metals Workshop

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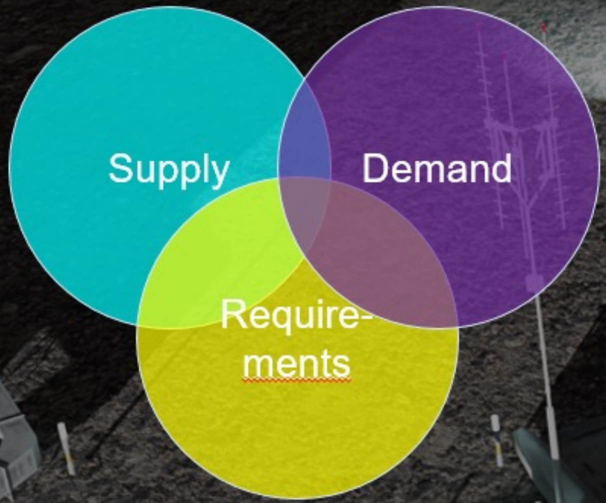
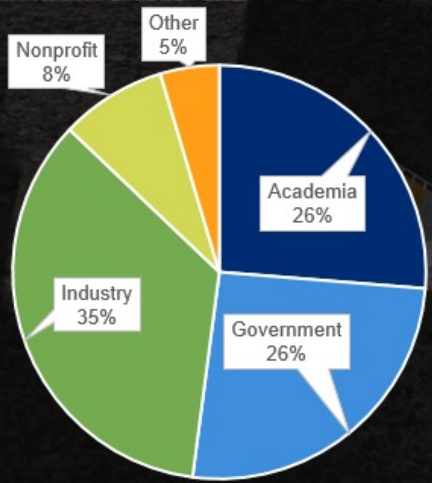
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



Virtual Workshop, 23 February 2022

230 attendees, 110 organizations



Summary:

- Initiated discussions to integrate lunar metal supply capabilities, construction needs, and user requirements.
- A “Lunar Proving Grounds” facility, where deployment and operation of systems can be rapidly tested and demonstrated, would enable a streamlined “test as you build” development approach. → Recommended to NASA and need to define better
- Industry need to develop business plans for their lunar activities both with and independent from NASA.
  - A workshop on defining needs/requirements and linking with construction: “Rebar to Roadway.” → More work is needed!
  - A lunar commercialization study. → Being considered
  - Development of manufacturing processes for the lunar surface.

Agenda

Introduction:

1100 - 1110: Athonu Chatterjee (LSIC E&C Lead) and Karl Hibbitts (LSUC ISRU Lead) – Workshop Objectives

NASA Speakers:

1110-1130: Mark McDonald, STMD Chief Architect – Vision Statement

1130 – 1215: NASA Panel

- Mark McDonald, STMD Chief Architect
- Niki Werkheiser, Director of Technology Maturation
- Jerry Sanders (ISRU), Principal Technologist, ISRU Lead
- Mark Hilburger (Excavation & Construction), Principal Technologist, E&C Lead

Supply side: Regolith Extraction

- 1220 – 1230: Lunar Resources – Elliot Carol
- 1230 – 1240: Sierra Space – Brant White
- 1240 – 1250: Airbus – Mark Kinnersley
- 1250 – 1300: Pioneer Astronautics – Mark Berggren
- 1300 – 1310: Terraxis - Geo Licciardello
- 1310 – 1320: Helios - Jonathan Geifman
- 1320 – 1330: Kilncore - Antoine Missout
- 1330 – 1350: Mini – Panel (all supply side speakers) – Q&A

Break 1350 – 1400

Demand side: Construction Needs and Drivers

- 1400 – 1410: Bechtel - Keith Churchill
- 1410 – 1420: Skidmore, Owings & Merrill – Daniel Inocente
- 1420 - 1430: XArc/Astroport – Sam Ximenes
- 1430-1440: Redwire Space – Kari Abromitis
- 1440 – 1450: Relativity Space – Josh Brost
- 1450 – 1500: Keystone - Bryant Walker
- 1500 – 1520: Mini – Panel (all demand side speakers) – Q&A

Break: 1520 – 1530

Combined Panel Discussion: 1530 – 1630

Wrap Up: 1630 – 1645

Summary Report available on the ISRU Meetings and Events Page

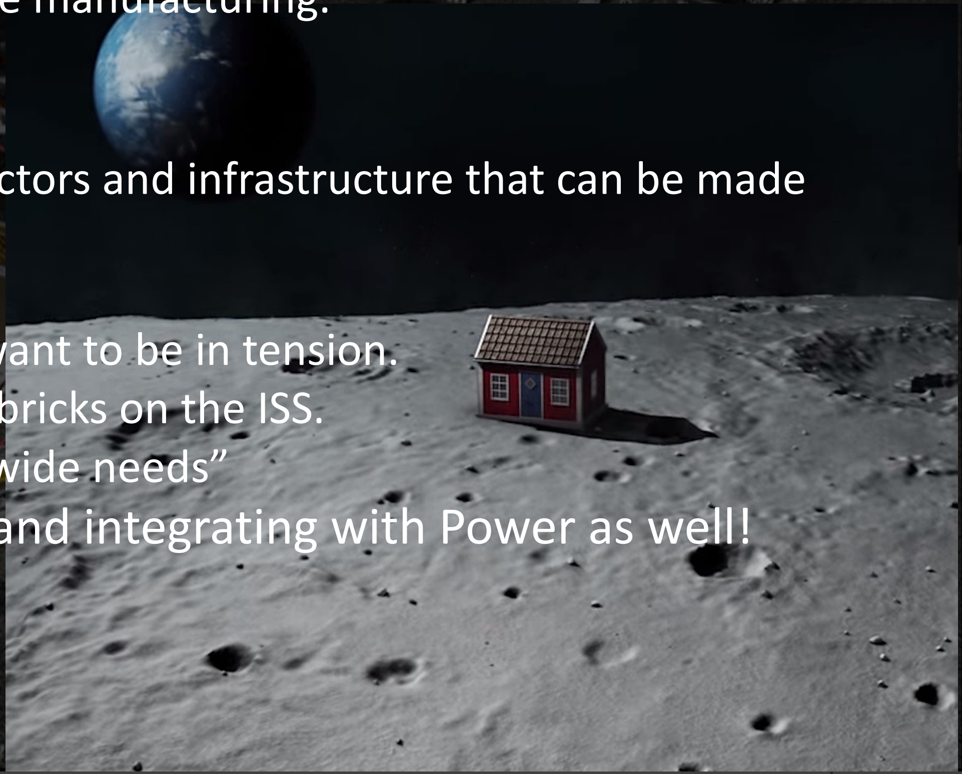
Vision Setting

Representing the major O_2 and Metal extraction technologies both domestic and international

Representing a significant portion of the potential customers of metal products

LSIC | Lunar “Regolith to Rebar” Metals Break-out at LSIC Spring Meeting

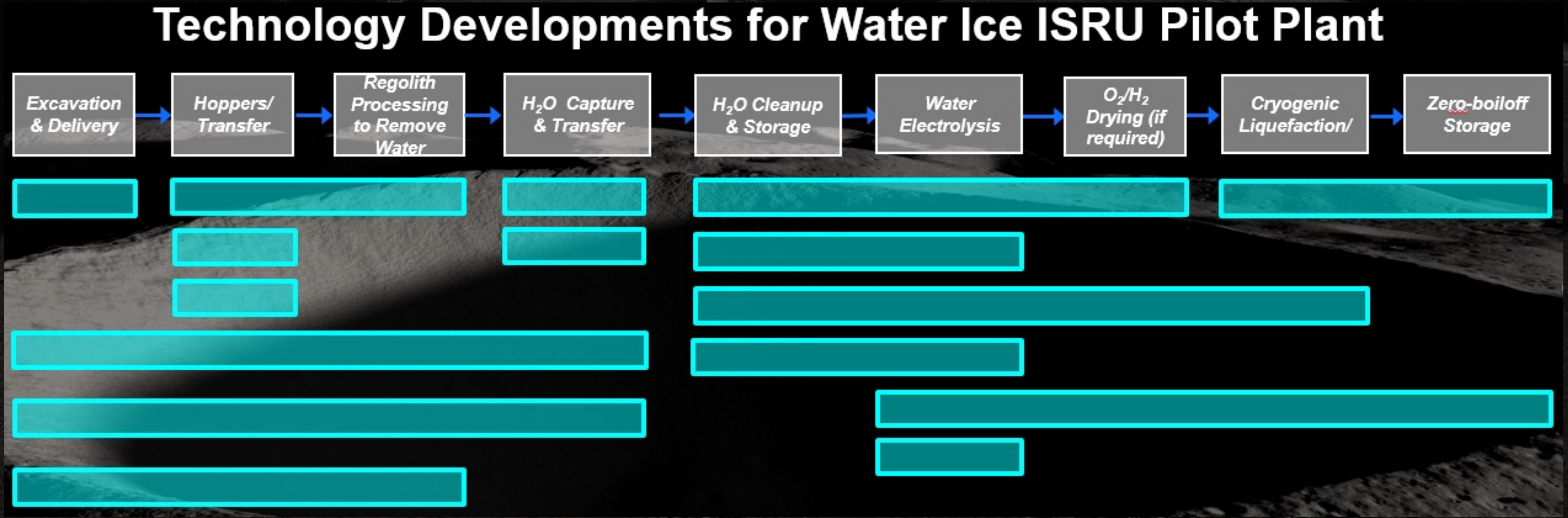
1. Extraction of metals from regolith is still in its infancy. Get the architects talking to the technologists more.
2. Each of the five O2 extraction technologies presented at R2R have a potential capability in terms of providing metals: MRE, carbothermal, MSE, vapor pyrolysis, hydrogen reduction.
3. Operations and Maintenance needs to be addressed.
   - Autonomy and telerobotics can play a role. Australian LNG and other mining companies are pioneering this.
   - OSAM: On-orbit Servicing and Maintenance. Can learn a lot from space manufacturing.
   - Try not to reinvent the wheel.
4. How to Use the materials has a long way to go.
   - Most ‘architectural’ companies are proponents of aluminum as connectors and infrastructure that can be made in-situ on the surface. But what purity is needed?
   - Basalt fibers may be good to use.
   - Stresses for construction are low, although a pressurized habitat will want to be in tension.
   - Standards? IEEE? Testing standards? MMPDS. Three different power bricks on the ISS.
   - Specific applications/parts that should be identified as near-term or “wide needs”
5. Have another workshop! R2R part 2! Setting needs/requirements and integrating with Power as well!



Enabling technology Development for Water-ice Processing

Help water ice extraction and processing technologies to be as successful as possible by looking at it from a system-level perspective.

<u>Every water-ice processing technology category has at least one funded development</u>



Recommending Water-ice Prospecting be Prioritized

A Recommendation to NASA to Leverage SMD Mission

Lunar Surface Innovation Consortium ISRU Focus Group Recommendation for Coverage of the Proposed Artemis Landing Sites by the Lunar Trailblazer Mission

March, 2021

Karl Hibbitts, Michael Nord, Kirby Runyon; Johns Hopkins University Applied Physics Laboratory

Bottom line up front

- Better knowledge of water-ice locations & abundance is needed in order to effectively plan the extraction of lunar water .
- Infrared reflectance observations of the type conducted by Lunar Trailblazer will provide high spatial resolution, high reliability maps of surficial water, in both illuminated areas and PSRs.
- TrailBlazer is a SMD mission and therefore its priorities are science-focused. However, water ice data in areas around potential Artemis landing sites (including PSRs) should also be prioritized.

Enabling Water-ice Prospecting

A feasibility study on 5-km south pole periapsis orbits submitted to ASCEND 2022

<u>Prospecting Lunar Polar Ice from Low-Altitude Orbits.</u>
J. Shannon, C.A.. Hibbitts, K. Runyon, M. Nord, and J. Berdis
Johns Hopkins Applied Physics Laboratory, Laurel, Md, 20723, United States, Jackson.Shannon@jhuapl.edu

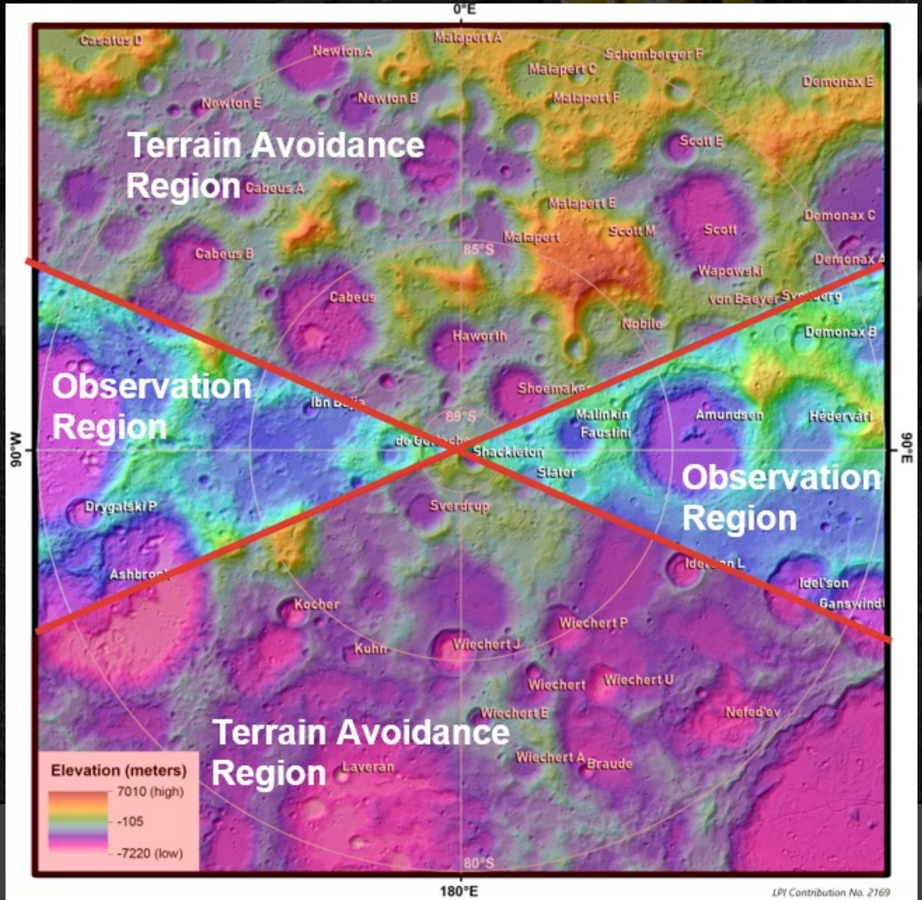


Figure 1. Lunar south pole terrain. Potential observation regions exist in low-altitude terrain regions.

Future Efforts – LSIC ISRU

- Enabling More and improved Networking for the ISRU community, expanding into other FGs.
- Recommendations given to NASA or being considered:
  - Conduct Commercialization study - recommended
  - Develop Lunar Proving Grounds - recommended
  - Defining lunar surface ISRU requirements and needs – TBD
- Will continue to help enable the development of technology for O_2 extraction.
- Will continue to help determine how to conduct H_2O ice prospecting missions.