Lunar Site Selection Criteria for In-Situ Resource Utilization (ISRU)

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Site Selection For ISRU In a Nutshell

- The ISRU Project Can Produce All The Products Currently Specified In the Architecture
- The ISRU Project Can Supply The Quantities Of Each Product Required In The Amount Of Time Available
- The ISRU Project Can Supply It Anywhere You Decide to Go On The Lunar Surface

Any Questions?

What is Lunar In-Situ Resource Utilization (ISRU)?

ISRU: In-Situ Resource Utilization

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

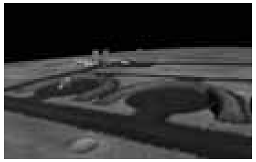
In-Situ Lunar Resources

- **'Natural' Lunar Resources:**
  – Regolith, minerals, metals, volatiles, and water/ice
  – Sunlight, vacuum, thermal gradients/cold sinks
- **Discarded Materials**
  – LSAM descent stage fuel residual scavenging, tanks, etc. after landing (with Power)
  – Crew trash and waste (after Life Support processing is complete)

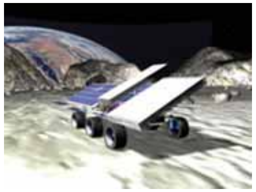
Lunar ISRU Products and Services

- **Mission Consumable Production**
  – Complete Life Support/Extra Vehicular Activity closure for Oxygen (O_2) and water
  – Propellant production for robotic and human vehicles
  – Regenerate and storage life support and fuel cell power consumables (in conjunction with Life Support and Power)
- **Site Preparation and Outpost Deployment/Emplacement**
  – Site surveying and resource mapping
  – Crew radiation protection (In-situ water production or bulk regolith)
  – Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
  – Area and road clearing to minimize risk of payload delivery and emplacement
- **Outpost Growth and Self-Sufficiency**
  – Fabrication of structures that utilize in-situ materials (in conjunction with Habitats)
  – Solar array, concentrator, and/or rectenna fabrication (in conjunction with Power)
  – Thermal energy storage & use from processed regolith (in conjunction with Power)
  – Production of feedstock for fabrication and repair (in conjunction with Sustainability)









Site Selection Criteria for ISRU

- Resource availability for main products of interest (Near & Long-term)
  - Oxygen production
  - Hydrogen/water
  - Solar wind volatiles
  - Metals/silicon for construction and in-situ manufacturing and repair
- Resource concentration and distribution
  - Location of resource(s) of interest w/ respect to Outpost location
- Local topography and rock/boulder distribution
  - Ease of excavation
  - Ease of resource delivery to processing units
  - Ease of communication and oversight
- Power Availability
  - Highly desirable to minimize # of startup/shutdown cycles)
- Environmental conditions
  - Near permanent sunlight, Diurnal Cycles, Shadowed Craters?

Resource Availability & Near/Long-Term Needs

- From LAT Phase I & II, near-term ISRU product need is oxygen (~ 2 MT/ year)
  - The baseline low risk-low yield process selected is hydrogen reduction of regolith; This process reduces iron-oxide with hydrogen to create water so areas of high iron concentration are of interest
  - The higher efficiency/higher risk option is carbothermal reduction of regolith; This process reduces the silicates with carbon or carbon monoxide. Areas of high silicate concentration are of interest
- Another near term enhancement would be water production. (~ 1MT/year)
- Long-term product of interest is propellants for transportation systems (oxygen, hydrogen, and possibly methane)
  - Polar regions containing high hydrogen concentrations are of main long-term interest since hydrogen, water, and other volatiles (methane, ammonia, etc.) may be present in concentrations high enough for efficient extraction and processing
  - Regions containing high pyroclastic glass material may be of interest since Apollo glass samples were shown to contain significantly more solar wind volatiles than bulk regolith
- Sustained human presence will also require in-situ repair and manufacturing capabilities to minimize logistics and loss of mission/crew issues. In-situ manufacturing might require powdered metals, ceramics, and plastics
  - Regions of high iron, titanium, silicon, and aluminum concentrations are of interest.
  - These materials also line up with oxygen extraction resource needs as well.

Site Selection Based on Resources

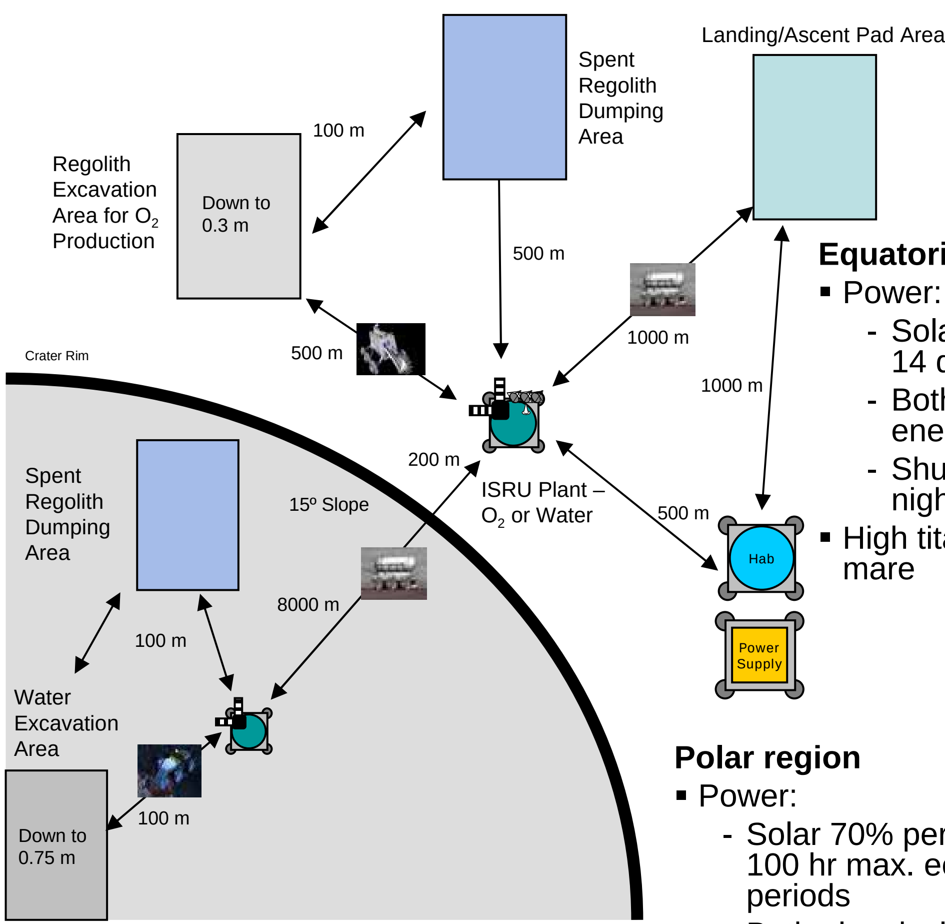
- ISRU site selection and ranking based on combination of resource available and ease of ISRU processes required to excavate resources and extract usable products.

	ISRU Site/Resource	*Rationale*
1	South Lunar Pole: Hydrogen, environment	Presence of hydrogen, water, and/or other hydrogen-baring molecules (NH_3, CH_4, etc.) could minimize need for oxygen extraction from regolith and enable in-situ hydrogen or hydrocarbon fuel production. Resource extraction through simple regolith heating, but does require excavation capabilities at 40K. Environmental factor of almost permanent sunlight and shadow could help ISRU and propellant storage processes and minimize need for start-up/shutdown operations associated with equatorial sites.
2.	Aristarchus plateau: Pyroclastic glass, solar wind volatiles, in-situ solar power production	Similar rational to High Titanium ores. Pyroclastic glass may also be easier to excavate and transfer.
3	NW-W Tranquililatis: High Titanium (iron), solar wind volatiles, in-situ solar power production	Oxygen extraction from high titanium ores utilizes lowest energy process. New work in fused salt electrolysis raises oxygen extraction percentage compared to hydrogen reduction. High titanium ores also contain highest concentrations of deposited solar wind volatiles.
4	North Lunar Pole: Hydrogen, environment	Similar rationale to South Lunar Pole. Compare and contrast hydrogen bearing areas between poles to determine best terrain, resource concentration, and regolith properties for final Outpost site selection
5	Near-equatorial highlands: Iron-poor, aluminum rich highlands	Possible interest in aluminum, calcium, and silicon extraction for long-term fabrication and construction of power and habitat infrastructure
6	Mare Crisium: High iron, low titanium regolith	Oxygen extraction from iron oxide.

ISRU Operation Overview

ISRU: In-Situ Resource Utilization

Level 0 Outpost ISRU Operation Requirements



Equatorial region

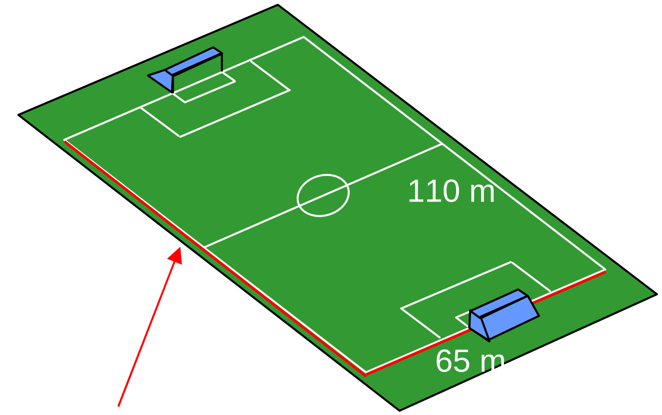
- Power:
  - Solar 50% per year with 14 day/night cycles
  - Both electrical and solar energy from sun
  - Shutdown during lunar night for maintenance
- High titanium/iron oxide mare

Permanently Shadowed Crater

- Upper 30 cm of regolith is likely desiccated
- 1.5% by mass water content. Regolith is loose and unconsolidated
- Power: Nuclear, cable, or power beamed for elements that stay in the crater

Polar region

- Power:
  - Solar 70% per year with 100 hr max. eclipse periods
  - Both electrical and solar energy from sun
  - Shutdown during eclipse periods for maintenance
- Highland regolith (iron poor)



10 MT of oxygen per year requires excavation of a soccer field to a depth of 0.6 to 8 cm! **(1% & 14% efficiencies)**

Excavation rates required for 10 MT O_2/yr production

- Hydrogen reduction at poles (~1% extraction efficiency): 150 kg/hr
- Carbothermal reduction (~14% extraction efficiency): 12 kg/hr
- Electrowinning (up to 40%): 4 kg/hr

Site Selection Based on ISRU Operations

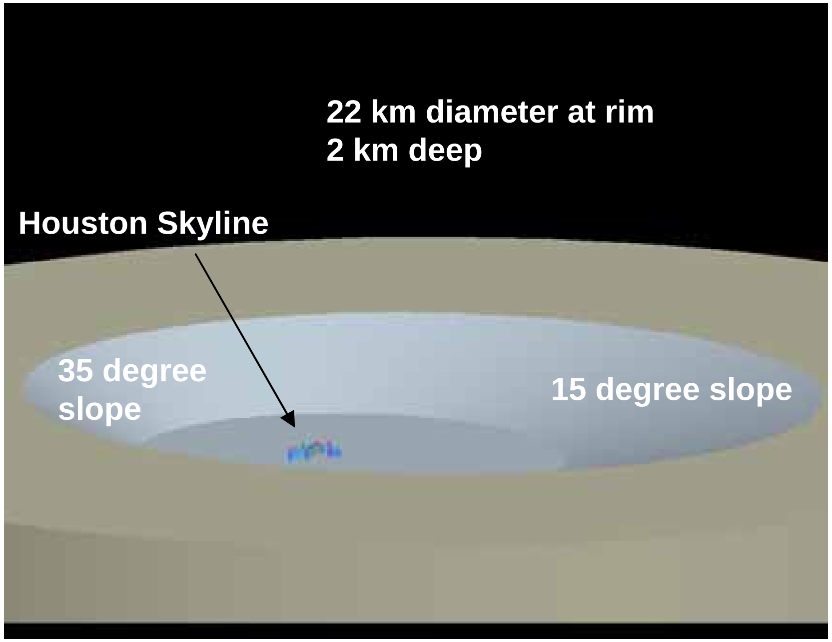
- The ease, efficiency, and benefit of ISRU is highly dependant on not just whether the resource is available but how ISRU operations fit into the Outpost. ISRU Operations are highly dependant on:
  - Location and concentration of resource of interest
  - Local topography
  - Local solar and thermal environmental conditions

- For early ISRU oxygen production (<10 MT/yr) using hydrogen reduction from regolith, ISRU operations favor:
  - Large, relatively flat areas of low rock/boulder concentrations so low energy excavation of top 8 cm of loosely consolidated regolith is possible
  - Locations of high solar concentration and duration:
    - Minimizes shutdown cycle number and duration
    - The bulk of oxygen production energy is associated with regolith heating, so solar concentrators can significantly reduce the electrical power need associated with ISRU oxygen extraction from regolith
  - Locations of moderate topography changes between Habitat, landing area, ISRU excavation area, and ISRU plant to facilitate:
    - Regolith movement to/from ISRU plant
    - Oxygen transport to/from ISRU plant to habitat and/or landing area
  - Locations of high iron-oxide concentration are not as important for low production rates since excavation and processing amounts are reasonable, even for polar locations with 5% iron oxide by weight.

Site Selection Based on ISRU Operations

- For long-term ISRU production needs (propellants and manufacturing feedstock)
  - Locations of high hydrogen concentration along with reasonable to moderate topography (transportation pathway) between the resource and processing plant are desired
  - High solar concentrations may not be as important if nuclear power is available. This may be requirement already for operation in permanently shadowed regions if this is where the resource of interest is located.
  - Further evaluation of pyroclastic glass distribution and solar wind volatile content may be warranted if access and extraction of polar hydrogen in permanently shadowed craters is deemed too difficult (ex. Shackelton crater analogy)

Model of Dawes Crater (Shackelton analog)



Site Selection w/Expanded ISRU Definition

- Expanding the ISRU "raw materials" to include scavenging from the landers and habitat may allow an easier solution to meeting Outpost needs

- Oxygen production still makes sense from the regolith.
  - (Life support loop can't be closed 100%)

- Small scale Water and Methane production on the moon may not end up being site dependent
  - Initial studies indicate that it may be possible to produce all the water needed by the Outpost by scavenging hydrogen from the Descent stage.
    - We will still require a topography that allows a logistics module to mate with the Descent stage.
  - If crew trash can be processed to extract the elemental components (significant carbon) then a reasonable quantity of methane could be produced in conjunction with the close loop life support system.
- If the role of ISRU grows to include propulsion, then a lunar source of hydrogen will be required.
  - That drives us to consider the poles due to the elevated hydrogen concentrations
  - But we will not know the practicality of polar hydrogen until we have a robotic mission to test for the availability and recoverability of the lunar hydrogen,

Concluding Remarks

- Oxygen is the current Architecture's main product of interest. (~2MT per year)
  - We have processes that can work anywhere on the surface
- Water is the second most desirable product (~1MT per year)
  - Polar location needed if we are to produce from the regolith
  - Scavenging appears to be an easier option until demand grows significantly
- Area's of high iron concentration are desirable
  - Allows us to use the "safe bet" oxygen production process H_2 reduction
  - Low iron concentration sites still viable but with higher excavation rates
- Topography is a consideration
  - Excavation is more difficult in a boulder strewn field
  - Ease of access to the Outpost for delivery of products
- Polar Locations suit ISRU the best unless nuclear power is available
  - near continuous operation, moderate temperature swings
- Equatorial regions harder, but products of interest can still be delivered.