NASA Oxygen and Water Production Architectures for Early Reusable Lander

Lunar ISRU Workshop
July 17, 2019

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GRC COMPASS Team
Lunar ISRU Presentation Overview

- ISRU Overview for Human Lunar Architecture
- Oxygen from Regolith
- Polar Water Prospecting & Mining
- Sustainable Lander and ISRU
- Backup
ISRU Overview for Human Lunar Architecture
Goals for Initial and Long Term Lunar ISRU
Consumable Production

HEOMD – Human Lunar Lander Reusability and Sustainability
- Early ISRU: Make 10 mT/yr oxygen from lunar regolith to fuel lander by 2030 if not sooner
- Sustainable ISRU: Mine 15 mT/yr water in polar craters to fuel reusable landers by TBD

STMD – Strategic Technology Formulation
- Meet strategic thrusts for Go, Land, Prosper by addressing Key Capability Challenges for Regolith to Oxygen, Lunar Ice to Water, and Water to Cryogenic Propellant

SMD – Lunar Science and Resource Understanding
- Utilize Commercial Lunar Payload Services (CLPS), instruments, and missions to advance understanding of the Moon, especially volatiles in permanently shadowed regions at the poles for science and exploration

American Leadership and Commercialization of Space
- Promote SPD-1: Reinvigorating America’s Human Space Exploration Program to lead an innovative and sustainable program of exploration with commercial and international partners (for long-term exploration and utilization of space resources)

ISRU must first be demonstrated on the Moon before it can be mission-critical.
Lunar ISRU Mission Consumables: Oxygen from Regolith vs Polar Water

- **Oxygen from Regolith**
  - Lunar regolith is >40% oxygen (O\(_2\)) by mass
  - Can be incorporated into the architecture from the start with low-moderate risk
  - Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)
  - Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions

- **Water (and Volatiles) from Polar Regolith**
  - Form, concentration, and distribution of Water in shadowed regions/craters is not known
  - Cannot be incorporated into the architecture from the start with low to moderate risk
  - Provides 100% of chemical propulsion propellant mass
  - Polar water is “Game Changing” and enables long-term sustainability
    - Strongly influences design and reuse of cargo and human landers and transportation elements
    - Strongly influences location for sustained surface operations

**Current Plan:** Develop and fly demonstrates for both lunar ISRU consumable approaches
- Develop oxygen extraction to meet near term sustainability objectives
- Utilize orbital missions and early lunar surface missions to understand and characterize polar environments, regolith, and water resources to address risks and technology needs
Oxygen Extraction from Regolith
Oxygen from Regolith Mineral Oxides – Comparison of Most Advanced Concepts

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen Reduction</th>
<th>Methane Reduction</th>
<th>Molten Oxide Electrolysis</th>
<th>Ionic Liquid Reduction</th>
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<tbody>
<tr>
<td>Resource Knowledge</td>
<td>Good - Orbital High Resolution &amp; Apollo Samples</td>
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<tr>
<td>Site Specificity</td>
<td>Moderate to High (Ilmenite &amp; Pyroclastic Glasses Preferred)</td>
<td>Low to Moderate (Iron oxides and Silicates)</td>
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<td>Temperature to Extract</td>
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*kg O₂/kg bulk regolith

Carbothermal Reduction
Mix carbon into molten regolith at >1650 °C to extract oxygen in the form of carbon monoxide/dioxide
Requires secondary reactor to convert CO/CO₂ to H₂O

Pros:
- **Will work on regolith anywhere on the Moon;** silicates are very abundant, especially at the Poles
- Higher yield (5 - 15 wt%) reduces excavation and transportation needs
- High TRL- 5; System ground tested
- Technologies highly relevant for Mars ISRU O₂ & CH₄ production

Cons:
- **High temperature and thermal energy** drives need for direct thermal technology (such as solar concentrators)
Assumed lander had 3.6 mT payload capability and all hardware needed to produce and store O₂ are on a single lander
- 2nd lander required to deliver mobile O₂ storage and transfer unit

Each ISRU module (there are two) produces 15.6 kg of O₂ per day (3500 mt O₂ per year per module)

ISRU plant, excavation zone, and dump zone form triangle with 100 m each leg

Each Excavator
- Provides 4 deliveries of 35 kg per day to ISRU plant (20 mins total per delivery)
- Provides 3 disposal runs of 40 kg per day to clear out the two ISRU modules (17 mins total per disposal run)
- Is charged every 4.5 days (1 kWhr discharged maximum 80% - 50 charge cycles per operating year)
- Operates via tele-operation/supervised-autonomy with a communication link through the lander to Gateway to Earth

Electrolysis subsystem converts H₂O into O₂ and H₂
- 0.65 kg/hr of O₂; H₂ recycled back to methanation reactor

Oxygen is liquefied and stored in the descent stage LO₂ tank (single system for all ISRU modules)
- 1.3 kg/hr of O₂ (total from two ISRU modules) liquefied and placed in lander tanks

Solar Concentrator: 22.2 kWth energy delivered to ISRU reactors (2) via fiber optic at 1800 °C

Electrical Power: 15 kWe (entire system, with 30% growth)
- Two Ultraflex arrays at 5.4 m diameter
- Regenerative fuel cell used for nighttime survival during ISRU standby mode (4.6 ‘winter’ months)
Oxygen from Regolith Concept of Operations

Two Landers to Deploy Full Scale Plant
- **Lander 1**: ISRU O₂ Production Plant, Excavators, & Power System
- **Lander 2**: O₂ Tanker: O₂ Tanks & Mobile Platform

**Options**: Where O₂ is liquefied and stored during production
- Descent tanks
- Separate tank as payload
- Mobile tanker
Oxygen from Regolith – Full Scale System

Point of Departure Carbothermal Reduction (7+mT O₂/year)

Spudis Point, Worst Landing Divergence, 2029, 10 m height, 30 m/pixel LOLA

50 to 60 extra days 225 days

NOTE: Overall Concentrator height is 11.65 m with a width of 5.24 m

NOTE: Both solar arrays create a width of 15.34 m
## Oxygen from Regolith – Full Scale System Systems Rollup

### MEL Summary: Case 2 ISRU CD-2018-162

<table>
<thead>
<tr>
<th>Main Subsystems</th>
<th>Bus</th>
<th>ISRU System</th>
<th>Excavator System</th>
<th>TOTAL</th>
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**Element Total**

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<tr>
<th></th>
<th>Basic Mass (kg)</th>
<th>Basic Mass (kg)</th>
<th>Basic Mass (kg)</th>
<th>Total Basic Mass (kg)</th>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

| **Element Dry Mass (no prop, consum)** | 1509.9 | 1021.1 | 212.0 | 2743.0 |
| **Element Propellant** | 0.0 | 0.0 | 0.0 | 0.0 |
| **Element Mass Growth Allowance (Aggregate)** | 281.9 | 179.4 | 43.6 | 504.8 |
| **Additional System Level Growth (For 30% tot)** | 171.1 | 127.0 | 20.0 | 318.1 |

**Total Wet Mass with 30% Growth**

<p>| | | | | |</p>
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Total payload < 3600 kg lander capability
# Oxygen from Regolith – Full Scale System

## Powered Equipment List

(values are before 30% growth)

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<tr>
<th>Description</th>
<th>Power Mode 1</th>
<th>Power Mode 2</th>
<th>Power Mode 3</th>
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</table>
## Oxygen from Regolith – Full Scale System

### Master Equipment List

<table>
<thead>
<tr>
<th>Description</th>
<th>Basic Mass</th>
<th>Growth</th>
<th>Growth</th>
<th>Total Mass</th>
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<td><strong>Excavator</strong></td>
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<td>30%</td>
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<td>15.6</td>
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**Point of Departure Excavator**

85”
Oxygen from Regolith – BBC

Carbothermal Reduction w/ Solar Concentrator

- Carbothermal Subsystem: 484.1 kg
  - Reactor based on design by Orbital Technologies Corporation (now part of Sierra Nevada Corp.) scaled down 3.5 mt O₂ / year
  - Reactor bed was re-sized for 14 melt zones
  - Each reactor requires 14 processing zones
  - Assumed 12.1% yield at 1800 °C melt temperature

- Water Electrolysis Subsystem: 122.5 kg

- Solar Concentrator: 221.2 kg
  - Requirement: 11.1 kWth energy delivered to each of two ISRU reactors via a 10 m fiber optic run
  - Inflatable: lightest (0.2 kg/m²), but less accurate – requires secondary concentrator to achieve comparable concentration ratios

- Oxygen Liquefaction/Transfer Subsystem: 135.8 kg

Total Mass: 742.4 kg
Excavator Concept
- Excavator design based on Astrobotic Polaris design
- Transverse bucket wheel delivers regolith into central holding tray
- 200 kg excavator tested in gravity-offloading tests
- Digging rate: 0.5 kg/sec
- Baseline driving velocity: 28 cm/s
- Demonstrated payload ratio: 25 – 50%

Mass Breakdown:
- 128 kg per excavator x 2 = 256 kg (with growth)

Power Breakdown:
- 1 kW-hr battery discharged maximum 80% (50 charge cycles per ‘year’)
- Charge with 100 W for 10 hours using inductive charge plate housed on floor of lander box

<table>
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<tr>
<th>Description</th>
<th>QTY</th>
<th>Unit Mass</th>
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<td>(kg)</td>
<td>(kg)</td>
<td>(%)</td>
<td>(%)</td>
<td>(kg)</td>
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<td>Excavator System</td>
<td>212</td>
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<td>44</td>
<td>256</td>
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<tr>
<td>Excavator</td>
<td>200</td>
<td>20%</td>
<td>40</td>
<td>240</td>
<td></td>
<td></td>
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<tr>
<td>Excavation and Processing</td>
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<td>40</td>
<td>240</td>
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<td></td>
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<td>Mobile Excavator with transverse bucket wheel</td>
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<td>40</td>
<td>240</td>
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<td></td>
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Polar Water Prospecting & Mining
Direct evidence of surface exposed water ice in PSRs

Evidence of Hydrogen (Lunar Prospector Neutron Spectrometer)

Access to Sunlight for Infrastructure, Processing, Landing

Reasonable terrain to Permanently Shadowed Crater (PSR)

Nearby PSR with strong indications of water (H₂, Thermal Stability, Surface Frost)

Earth visibility (need is reduced with communications satellite)
## Potential South Pole Landing Sites

‘Spudis Ridge’ South Pole

### ISRU Ridge Site *Current Baseline*

<table>
<thead>
<tr>
<th>PSR Site</th>
<th>Distance, m</th>
<th>Max Slope, deg</th>
<th>Approx. dia of PSR ice region, m</th>
</tr>
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<tbody>
<tr>
<td>PSR 1</td>
<td>9105</td>
<td>14</td>
<td>1000</td>
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</tr>
<tr>
<td>PSR 5</td>
<td>6688</td>
<td>21</td>
<td>500</td>
</tr>
</tbody>
</table>

### Human Landing Site

- Full Power Generation
- ISRU Water Processing, Liquefaction & Storage
- PSR Ice Mining

### Table of Potential South Pole Ridge Sites

<table>
<thead>
<tr>
<th>PSR 1 straight</th>
<th>Distance, m</th>
<th>Max Slope, deg</th>
<th>Approx. dia of PSR ice region, m</th>
<th>Ridge Longitude</th>
<th>Ridge Latitude</th>
<th>PSR Longitude</th>
<th>PSR Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR 4 straight</td>
<td>6500</td>
<td>18</td>
<td>1500</td>
<td>-137.34 (222.64)</td>
<td>-89.45</td>
<td>-158.79</td>
<td>-89.57</td>
</tr>
<tr>
<td>PSR 4 Ridgeline</td>
<td>6850</td>
<td>15</td>
<td>1500</td>
<td>-158.73</td>
<td>-89.58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ice stability depth (Diviner)
- Arrow indicates ridge (sunlight) hardware location
- White areas are surface stable ice
PSRs Near ‘Spudis Ridge’ and Traverse Paths
Lunar Polar Ice Mining Architecture Options

**Lunar Polar Water Mining requires:**
- Assessable resources in permanently shadow region (PSR)
- Nearby long-duration sunlit area for ISRU and human mission infrastructure
- Sustained communications with Earth (direct or relay)

**Options involve Extraction Process and what Hardware/Operations are performed in PSR**

1. Icy Regolith is transported to sunlight ridge where it is processed and converted to propellant

2. Icy Regolith is processed in PSR; Power is required in PSR
   - Water is delivered to Propellant production and storage at sunlight ridge
     
     A. Mobile excavators deliver to a stationary extractor in PSR. Water is delivered out of PSR to production plant using a mobile water tanker.
     
     B. Excavation and water extraction is housed on mobility platforms that remain in PSR. Water is delivered out of PSR to production plant using a mobile water tanker.

3. Icy Regolith Excavation/Processing Plant is Mobile
   - One mobility platform excavates, extracts water, and delivers water outside PSR.

4. In-situ: Water is removed from the soil without excavating soil
   - Regolith Process and Power are inside PSR; Water is delivered outside of PSR for Water Processing & Product Storage

‘Best’ Architecture is predicated on
- Mining site selected: resource location and infrastructure location
- Resource properties: hardness and resource concentration, depth, and distribution
Lunar Polar Ice Mining Architecture Options & Technologies

1. Icy Regolith is transported to sunlight ridge where it is processed and converted to propellant

Traverse distance and time deemed not reasonable for Study

2. Icy Regolith is processed in PSR; Power is required in PSR Plant.

A. Stationary water extraction

B. Mobile water extraction

3. Icy Regolith Excavation/Processing Plant is Mobile

4. In-situ: Water is removed from the soil without excavating soil
Polar Water Mining Ground Rules & Assumptions

- 10 mT of Oxygen and 1.7 mT Hydrogen produced in 1 year
  - 1 yr = 225 days, consecutive solar availability
  - Need 15.3 mT of Water; hydrogen is driving requirement (11.3 mT water need to give oxygen)

- Location: South pole, Shackleton area ("Spudis" ridge)
  - Propellant plant is in Sunlight location. Water resource is some distance away in PSR
  - Environmental conditions (including traverse distances, slopes, temperatures) at notional Sunlight and PSR locations from Diviner data in Quickmaps software

- State power needs (thermal and electrical) for both Ridge and PSR but mass of power system is NOT included

- Propellant production plant is assumed same for all architectures and located on ridge in sunlight
  - This plant includes everything downstream of (and including) water cleanup (eg. water cleanup, electrolyzer, storage tanks)
  - Transfer of propellant to descent stage is not addressed

- Deployment of equipment is NOT considered in this trade, even though it may influence trade (particularly when PSR emplacement is needed)

- Thermal management is only considered on relevant component level (eg tanks) not on system scale
Polar Ice Mining Study Goals & Approach

Goals

- Trade the different architecture scenarios for Lunar Polar Water ISRU to identify a baseline for a COMPASS study
  - Outcome will also be used for technology development plans, prospecting needs, CLPS demos, etc.
- Examine different Architecture options:
  - Identify baseline hardware for each option
  - Estimate Mass & Power needs for each
  - Identify top level ConOps (needed for mass/power estimates)
- Landing Site set for this study so that terrain, resource availability, and environment conditions can be fixed

Approach: Preliminary study

- Choose baseline hardware/technologies for each architecture
  - Use actual hardware and empirical data when possible (higher TRL hardware will be selected when available)
  - Hardware selected is not optimized solution, selected based on highest fidelity models/hardware
- Examine scenarios based on the following key parametrics
  - Number of trips into the PSR. Fewest number of trips is preferred, but may not be most optimum mass/power solution
  - Water concentration in soil
  - ConOps timelines: Trades include processing time, recharge time, traverse time, etc. Balance these to give a reasonable ConOps
Polar Water Mining Concept Comparisons

- At least 8 concepts are currently being explored including:
  - Excavation w/ Auger dryer
  - Heated coring auger
  - Microwave heating
  - Heated Dome

- Application of concepts are highly dependent on:

  **Resource Depth Access:** How deep the water resource can be for a given concept to work.

  **Spatial Resource Definition:** Defines the spatial resolution of the resource location needed for successful deployment.

  **Volatiles retention:** How much of the volatiles in the raw material are captured vs lost to the environment.

  **Material Handling:** How much interaction is required with the regolith.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Architecture Option</th>
<th>Status</th>
<th>Resource Depth access</th>
<th>Spatial Resource definition</th>
<th>Volatiles retention</th>
<th>Material Handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger Dryer</td>
<td>X</td>
<td>Breadboard Laboratory hardware</td>
<td>Moderate (cm)</td>
<td>10s of Meters</td>
<td>Low-moderate</td>
<td>High</td>
</tr>
<tr>
<td>Microwave Vessel</td>
<td>X ?</td>
<td>Breadboard Laboratory hardware</td>
<td>Moderate (cm)</td>
<td>10s of Meters</td>
<td>Low-moderate</td>
<td>High</td>
</tr>
<tr>
<td>Microwave Zamboni</td>
<td>X X</td>
<td>Concept Study</td>
<td>Surface</td>
<td>10s of Meters</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Vibrating Tray</td>
<td>X X</td>
<td>Breadboard Laboratory hardware</td>
<td>Moderate (cm)</td>
<td>10s of Meters</td>
<td>Low-moderate</td>
<td>High</td>
</tr>
<tr>
<td>Coring Auger</td>
<td>X X</td>
<td>Breadboard Laboratory hardware</td>
<td>Deep (m)</td>
<td>10s of Meters</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Heated Dome</td>
<td>X</td>
<td>Concept Study</td>
<td>Surface</td>
<td>Meter</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Heated batch [Resolute EBU]</td>
<td>X ?</td>
<td>Field demonstrations</td>
<td>Moderate (cm)</td>
<td>10s of Meters</td>
<td>Low-moderate</td>
<td>High</td>
</tr>
<tr>
<td>Water Jet/Dome</td>
<td>X</td>
<td>Concept Study</td>
<td>Moderate (cm)</td>
<td>Meter</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
2A. RASSOR with SCD

For baseline scenario 7/10/19: 5% water content, 22 trips out of the PSR, 24hrs water transfer/recharge at sunlit ridge propellant plant.

Mass Breakdown:
- Excavator: Rassors (2): 86 kg each
- Water extraction: Auger dryer (1): 104 kg*
- Water Tanker: Subscale Chariot (1): 1684 kg*
- Total Mass: 1.96 mT (metric Ton)
  *masses include 15% margin for structure, 20% margin for growth

Power Breakdown:
- PSR Power Total: 12 kW
  - Thermal power (water extraction): 11.7 kW
  - Electrical power: 0.3 kW
- ISRU plant (ridge) Power: 9.6 kW
  - Thermal power (water conditioning): 3.5 kW
  - Electrical power (battery recharge): 6.1 kW
- Total Power: 21.6 kW

Excavation Area/year (5% water by mass): 53.3 x 94 yds
2B. RP Rover with PVEx- BBC

For baseline scenario 7/10/19: 5% water content, 28 trips out of the PSR, 12 hrs water transfer/recharge at sunlit ridge propellant plant.

Mass Breakdown:
• Mobile water extraction (RP + PVEX*): 12 mT (300kg x 40)
• Water Tanker (Subscale Chariot): 1.99 mT*
• Total Mass: 14 mT (metric Ton)

*masses include 15% margin for structure, 20% margin for growth

Power Breakdown:
• PSR Power Total: 13.3 kW
  • Battery recharge only
• ISRU plant (ridge) Power: 10.4 kW
  • Battery recharge only
• Power Total: 23.7 kW

Excavation Area/year (5% water by mass): 53.3 x 32 yds
• 23000 holes
• 580 holes/PVEx
• 120 holes/day

RP Mobility Platforms each with 1 PVEx
Water Truck 0.27 scale Chariot Chassis
3. Mobile Water Extraction - BBC

For baseline scenario 7/10/19: 5% water content, 112 trips out of the PSR, 20 hrs water transfer/recharge at sunlit ridge propellant plant.

**Mass Breakdown:**
- Empty Chariot Chassis: 2458 kg
- Chariot Payload Subtotal: 1239 kg
  - PVEx Array (14): 210 kg
  - Additional batteries (in addition to chariot baseline): 3567 kg
- Condenser/Radiator/Storage Tank: 102 kg
- Margin (15% Structure, 20% Growth): 926 kg
- Total: 7.28 mT (metric Ton)

**Power Breakdown:**
- Chariot Battery Charging, 20hr: 46 kW

**Excavation Area/year** (5% water by mass): 53.3 x 32 yds
- 23178 holes/year
- 1655 holes/PVEx
- 197 holes/day
### Assumptions for Baseline Water Mining Cases

For this trade, parameters were chosen to give a moderate power/mass solution to each scenario (semi-optimization). The critical variables are shown for each scenario along with a description of their impact.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2a</th>
<th>2b</th>
<th>3</th>
<th>Impact of parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Water content</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>Higher number reduces mass &amp; power across the board</td>
</tr>
<tr>
<td>Number of mobility platforms</td>
<td>3</td>
<td>41</td>
<td>1</td>
<td>For 2a this number is calculated based on amount of soil needed. For 2b it set based on water processing time per PVEX (separate thermal model). For 3 the definition of the scenario is to have 1 platform.</td>
</tr>
<tr>
<td>Number of excavators</td>
<td>2</td>
<td>40</td>
<td>14</td>
<td>For 2b and 3 this is the number of PVEX systems, where for 2b there is one PVEX per mobility platform and in 3 all the PVEXs are mounted to one large mobility platform (Chariot)</td>
</tr>
<tr>
<td>Days in PSR</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>Semi optimized number based on mass/power.</td>
</tr>
<tr>
<td>Number of trips out of PSR</td>
<td>22</td>
<td>28</td>
<td>112</td>
<td>= days in PSR ÷ 225 days (total production time)</td>
</tr>
<tr>
<td>Recharge time in PSR</td>
<td>5hr</td>
<td>5hr</td>
<td>NA</td>
<td>A longer recharge time requires less power from the surface power source. Shorter recharge times allow for faster processing: potentially fewer mobility platforms and/or less water extraction energy (more time for processing = less power)</td>
</tr>
<tr>
<td>Recharge time at Ridge</td>
<td>24 hr</td>
<td>12 hr</td>
<td>20 hr</td>
<td>A longer recharge time requires less power from the surface power source. Choice is based on con-ops of system. These numbers are generally the longest time that can be afforded based on earlier assumptions.</td>
</tr>
</tbody>
</table>
PVEx is a heated coring drill from Honeybee robotics that combines excavation and water extraction into one tool. It is being considered for an early ISRU CLPS demo. The trade below highlights challenge of using this system for large scale ISRU.

**Key Assumptions**
- The drill is 5 in diameter, 0.75m. The diameter is larger than the current designed drill (2 in), which would increase production per drill over current SOA.
- The extraction efficiencies are based on empirical data from the SOA 2 in diameter unit.
- Water contents are the average over the entire core length. No distinction was made in the model depth distribution of water.

**Key Results:**

<table>
<thead>
<tr>
<th>Water Content</th>
<th>Total # drill holes</th>
<th>Drill holes per Day</th>
<th>Drill holes Per Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>23,000</td>
<td>103</td>
<td>1430</td>
</tr>
<tr>
<td>15%</td>
<td>7700</td>
<td>40</td>
<td>480</td>
</tr>
<tr>
<td>30%</td>
<td>3800</td>
<td>17</td>
<td>240</td>
</tr>
</tbody>
</table>

Wear/Life of drill bits may be ~100 holes per bit (rough estimate from Honeybee Robotics). The number of feasible bit changes over the life is TBD.
Trade (2A, 2B, 3) : Baseline Comparison

For this trade, parameters were chosen to give a moderate power/mass solution to each scenario (semi-optimization).

The ridge production plant is the system that processes water into propellants. Retrieval System are anything upstream of this.

- Scenario 2a is the best trade in terms of mass and power
  - Note that the Auger water extractor parameters were set to best case. However when using more conservative numbers 2a remains the lowest mass options while power is comparable (slightly higher) than 2b.
  - Only 2 Rassor systems are needed due to the throughput of the Auger water extractor and the conops timelines. Thus 2a could be done with only 3 mobility systems.
  - Over 90% PSR power requirement is direct thermal power (to extract water). Waste heat could be used to reduce electrical power required.

- Scenario 2b is highest mass due to large number of mobile excavators.
  - This could be improved if a different mobility platform is used. The RP mobility platform payload capacity and battery restriction are driving this.
  - Power is comparable to 2a but since water extraction is on a mobile platform all thermal energy must come from the battery. Thus power requirements show here are for battery recharges; frequent recharges offset the large thermal energy requirements.

- Scenario 3 has the benefit of one mobility platform and no PSR power requirements, but the cost is many trips in/out of the PSR and higher power requirement at the ridge
  - All the power required is to recharge the Chariot batteries. The recharge time is as high as the conops will allow to reduce this power draw.
  - The system must traverse the PSR every other day due to battery and mass restrictions.
The propellant production plant is the same in all scenarios and is located at a fixed location at the sunlit ridge site to leverage solar power option.

- The propellant production plant is same for all scenarios. It is located at the ridge site to leverage solar power.
- The largest mass and power is the hydrogen liquefaction system. This is a technology development need.
  - Consulted with CFM personnel to get specifications on existing cyrocooler systems that could meet needs.
  - Other conceptual systems offer better specifications and could be traded to improve estimates
- Water electrolysis remains one of the largest power draws
Any PSR of significant size requires mobility platform to traverse slopes of around 15 degrees
- Some shallower or near PSRs may contain water, but for this study only PSRs that have high probability of surface water were traded

All scenarios require multiple trips into PSRs. The capability of mobility platforms for this type of operations are unknown.
- The scenario with the fewest number of PSR trips still requires 10 trips at 5.25 km (includes margin for hazard avoidance) each way over 15deg slopes.
- Consistency of PSR material is unknown… fluffy material will pose greater difficulty
- Repeating traverses over same path raises significant trafficability concerns:
  • ‘Road’ construction (surface stabilization) may be needed in the long term
  • Alternative approach to water delivery to infrastructure outside of the PSR

Scenario 2A offers the best all around solution
- It requires the fewest number of PSR traverses with the lowest total mass. While PSR power is required, 90% of that power requirement is heat that some of which could be recuperated

Scenario 2B is the highest mass solution, but power is comparable to 2A.
- The number of PSR traverses can be moderate at ~20. But using the current parameters requires ~40 mobility platforms.

Scenario 3 has the benefit of one mobility platform and no PSR power source, but the cost is many trips in/out of the PSR
Polar Mining Study Takeaways

- Initial Results suggest that there are three main drivers for Water Mining Architecture viability
  - Method of Water removal from Crater
  - Method of Power in Crater
  - Method of Water Mining

- Location of Infrastructure (extended sunlit locations) and Location of Water (PSR) can strongly influences both Method of Water Mining and Method for Power in PSR
  - Long traverse distances can promote architectures with limited number of trips in/out of PSR for water removal
  - Power in PSR strongly preferred for reducing trips in/out of PSR

- Method for Water Mining will be highly dependent on concentration/depth of water resource
  - Hard material may require drilling; however, number of drill holes raises maintenance issues
Next Steps for Polar Water Mining Architecture Evaluation

- **Trade different PSR or Sunlight ridge site**
  - Locate ISRU production plant at human landing site
  - Evaluate a closer PSR region
  - Evaluate impact of a deeper water resource

- **Refine models.**
  - Working several improvements and corrections to existing models.
  - Consult with SMEs for subsystems to improve and verify our models: hydrogen liquefaction, mobility platform capabilities, thermal management for water extraction

- **Separate Thermal and Electrical power**
  - Indicate and define where utilization of waste heat is possible for each extraction method evaluated (already done in model but not shown graphically yet)

- **Compare to Oxygen extraction from Regolith systems**
  - Model the mass/power for a baseline system that extracts oxygen from ubiquitous minerals in surface regolith.
Backup
Full $O_2$ Production Excavator Overview

- Excavator design based on Astrobotic Polaris design
  - Transverse bucket wheel delivers regolith into central holding tray
  - 200 kg excavator tested in gravity-offloading tests
  - Digging rate: 0.5 kg/sec
  - Baseline driving velocity: 28 cm/s
  - Demonstrated payload ratio: 25 – 50%

- Scale down to ½ the mass
  - Assume same payload ratio and driving velocity
  - Assume digging rate cut in half

- Each ISRU module requires 130 kg of fresh regolith each day
  - Four deliveries per day (per module) at 35 kg / load for payload ratio of 35%

- Excavators also need to receive processed regolith (aka, slag) and dispose of in dump zone
  - Slag removed from reactor in form of solid half-spheres ~10 cm diameter
  - Multiple batches of slag nodules held in dump hopper until ready to be removed
  - 115 kg/day of slag (per module) (130 kg of fresh regolith less 12 % oxygen extracted)
  - Three disposal trips per day (per module) at 40 kg / load for payload ratio of 40%

### Table 3

Use of the 50 most illuminated spots in each pole. In addition to their location (longitude, latitude), we indicate their average illumination and visibility percentage at the surface and 10 m above the surface. Due to this height increase, their rank can change.

<table>
<thead>
<tr>
<th>Longitude</th>
<th>Latitude</th>
<th>At surface level</th>
<th>10 m above surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rank</td>
<td>Average solar illumination (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rank</td>
<td>Average solar illumination (%)</td>
</tr>
<tr>
<td>South pole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>222.69</td>
<td>-89.45</td>
<td>1</td>
<td>88.01</td>
</tr>
<tr>
<td>222.73</td>
<td>-89.45</td>
<td>2</td>
<td>88.68</td>
</tr>
<tr>
<td>223.28</td>
<td>-89.44</td>
<td>3</td>
<td>87.13</td>
</tr>
<tr>
<td>203.78</td>
<td>-89.78</td>
<td>4</td>
<td>86.71</td>
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<td>203.86</td>
<td>-89.77</td>
<td>5</td>
<td>86.76</td>
</tr>
<tr>
<td>120.37</td>
<td>-85.10</td>
<td>6</td>
<td>85.08</td>
</tr>
<tr>
<td>123.04</td>
<td>-88.81</td>
<td>7</td>
<td>85.09</td>
</tr>
<tr>
<td>197.02</td>
<td>-88.60</td>
<td>8</td>
<td>85.23</td>
</tr>
</tbody>
</table>

Note: White numbers from previous charts

Note: See next chart

Landing Zone (this study) "on ridge"
Maximum summer temperatures

- Arrow indicates ridge (sunlight) hardware location
- Blue spots are lowest temperature = highest likelihood for ice
Polar Water Extraction and Processing Options

Centralized ISRU Processing

- Soil Excavation
- Resource Preparation
- Soil Transfer
- Mobility Platform

Heated Auger (Bluefield Robotics)

Coring Auger (Bluefield Robotics)

Heated Dome (Colorado School of Mines)

Microwave Heating (JPL & GSFC)

Mobile Processing

- Soil Excavation
- Soil Transfer
- Mobility Platform

In Situ Processing

- Resource Access
- Water Extractor
- Water Capture
- Water Treatment
- Water Storage
- Water Cleanup
- Mobility Platform

Auger Dryer (NASA JSC)

Vibrating Tray (NASA JSC)

Water pump

Water Cleanup (de-ionization, etc.)

O2 Generator

Water Electrolysis

N2 Generator

Water Storage (condensation, etc.)
2A. Excavation & Processing in PSR w/ Power RASSOR/Extractor/Chariot

RASSOR excavates raw material and delivers to a stationary Auger dryer water extraction unit (co-located with power platform). A Chariot based water tanker collects water from water extraction unit and delivers it to ridge propellant production plant.

**Pros**
- Icy soil remains in PSR, volatiles loss upon excavation is limited
- Potentially several, smaller excavators making short trips
- Excavators are simple, single function

**Cons**
- Requires 2 mobility platforms
- Requires secondary power source in crater for water extraction plant and mobility recharging
- Dried material must be transported away
- Water must be transferred 2ce

**Baseline:**
- Excavator(s) continuously deliver batches of raw soil to a water extraction unit and remove processed soil. Excavators live in PSR. (NASA Rassor)
- Water extractor is at a fixed location in PSR, co-located with a power source. Extractor lives in PSR (NASA Auger Dryer)
- PSR power source for water extraction and battery charging. (Kilopower pictured, but not included in ISRU mass)
- Water extractor sends water vapor to a water tanker where it is condensed and stored.
- Water tanker periodically transports water out of PSR to propellant plant (NASA Chariot).
2B. Excavation & Processing in PSR w/ Power
PVEx/RP/Chariot

PVEx drills are mounted to RP mobility platforms. They extract and store water using a heated core drill. They navigate to a PSR power station where they recharge while transferring water to a chariot base water tanker. The water tanker delivers water to the ridge propellant production plant.

Pros

- Icy soil remains in PSR, volatiles loss upon excavation is limited
- Potentially several, smaller excavators making short trips
- Excavators are simple, single function

Cons

- Requires 2 mobility platforms
- Requires secondary power source in crater for water extraction plant and mobility recharging
- Dried material must be transported away
- Water must be transferred 2ce

Baseline:

- Heated coring drill: drill into regolith and heat in place to extract water. Water vapor travels up drill into onboard condenser. (Honeybee PVEX)
- Multiple mobility platforms each support one drill. Lives in PSR. (RP Rover)
- PSR power source for battery charging. (Kilopower pictured, but not included in ISRU mass)
- Each water extractor delivers water to larger water tanker during recharge periods
- Water tanker periodically transports water out of PSR to propellant plant (NASA Chariot)
Mobile platform excavates soil, extracts water, and stores water. Mobile platform operates in PSR and climbs out of crater to deliver to propellant plant.

Pros
- Icy soil remains in PSR, volatiles loss upon excavation is limited
- Dried soil can be immediately disposed

Cons
- Larger mobility platform required with a lot of functionality
  - Likely limited number of mobility platforms which increases failure modes
- Mobility platform must support power intensive processes (drying)

Baseline:
- Multiple Heated coring drills: drill into regolith and heat in place. (Honeybee PVEEX)
- Water vapor condensed in water tank (custom design)
- Mobility platform supports water tank, drills, and battery power source (NASA Chariot)
- System travels to production plant site out of PSR to deliver water periodically.