The Space Exploration Policy enacted by the US Congress in 2005 calls for the US National Aeronautics and Space Administration (NASA) to implement a sustained and affordable human and robotic program to explore the solar system and beyond; Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations; Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests. In 2006, NASA released the Lunar Architecture Study, which proposed establishing a lunar Outpost on the Moon with international participation to extend human presence beyond Earth’s orbit, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth’s economic sphere. The establishment of sustained human presence on the Moon for science and exploration combines the design, integration, and operation challenges experienced from both the short Apollo lunar missions and the build-up and sustained crew operations of the International Space Station (ISS). Apollo experience reminds developers and mission planners that hardware must operate under extremely harsh environmental and abrasive conditions and every kilogram of mass and payload must be critical to achieve the mission’s objectives due to the difficulty and cost of reaching the lunar surface. Experience from the ISS reminds developers and mission planners that integration of all hardware must be designed and planned from the start of the program, operations and evolution of capabilities on a continuous basis are important, and long-term life-cycle costs and logistical needs are equally or more important than minimizing early development and test costs. Overarching all of this is the need to implement efforts that are sustainable and affordable. One area NASA is developing that can significantly change how systems required for sustained human presence are designed and integrated, as well as potentially break our reliance on Earth supplied logistics, is In-Situ Resource Utilization (ISRU). ISRU, also known “living off the land”, involves the extraction and processing of local resources into useful products. In particular, the ability to make propellants, life support consumables, fuel cell reagents, and radiation shielding can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. Also, the ability to modify the lunar landscape for safer landing, transfer of payloads from the lander to an outpost, dust generation mitigation, and infrastructure placement and buildup are also extremely important for long-term lunar operations. While extra-terrestrial excavation, material handling and processing, and site preparation and construction may be new to NASA and other space agencies, there is extensive terrestrial hardware and commercial experience that can be leveraged. This paper will provide an overview of current NASA activities in lunar ISRU mining and construction and how terrestrial experience in these areas are important to achieving the goal of affordable and sustainable human exploration.
Presentation Topics

- We’re Going to the Moon Again?
- What is Lunar Mining – In-Situ Resource Utilization?
- What Are The Challenges to Lunar Mining?
- What is NASA Currently Doing?
NASA Lunar Exploration Overview
The Administrator shall establish a program to develop a sustained human presence on the moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations.
NASA'S PLAN FOR SPACE EXPLORATION

- Complete the International Space Station
- Safely fly the space shuttle until 2010
- Develop and fly the Orion crew exploration vehicle no later than 2015
- Return to the moon no later than 2020 and robotic program
- Implement a sustained and affordable human
- Use the moon to prepare for future human and robotic missions to Mars and other destinations
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration
COMPONENTS OF THE CONSTELLATION PROGRAM

Earth Departure Stage

Orion: Crew Exploration Vehicle

Ares V: Heavy Lift Launch Vehicle

Ares I: Crew Launch Vehicle

Lunar Lander
Launch Vehicle Comparisons

**Space Shuttle**
- Height: 56m
- Gross Liftoff Mass: 2040Mt
- 25Mt to LEO

**Ares I**
- Height: 98m
- Gross Liftoff Mass: 910Mt
- 22Mt to LEO

**Ares V**
- Height: 109m
- Gross Liftoff Mass: 3310Mt
- 53Mt to TLI
- 65Mt to TLI in Dual-Launch Mode with Ares I
- 131Mt to LEO

**Saturn V**
- Height: 111m
- Gross Liftoff Mass: 2950Mt
- 45Mt to TLI
- 119Mt to LEO

**Upper Stage**
- (1 J-2X)
- 127Mt LOx/LH₂

**Earth Departure Stage (EDS)**
- (1 J-2X)
- 226Mt lb LOx/LH₂

**Core Stage**
- (5 RS-68 Engines)
- 1410Mt LOx/LH₂

**S-IVB**
- (1 J-2 engine)
- 110Mt Lox/LH₂

**S-II**
- (5 J-2 engines)
- 450Mt LOx/LH₂

**S-IC**
- (5 F-1)
- 1770Mt LOx/RP

**Lunar Lander**
- Earth Departure Stage (EDS) (1 J-2X)
- 53Mt to TLI
- 22Mt to LEO

**Height & Mass**
- Space Shuttle: 56m, 2040Mt
- Ares I: 98m, 910Mt
- Ares V: 109m, 3310Mt
- Saturn V: 111m, 2950Mt
Transport 4 crewmembers to and from the surface
- Visits start with 7 days on surface
- Length of stays increases step-by-step
- Builds up to 6 month lunar outpost crew rotations

Global access capability
Return to Earth anytime
Deliver about 16 metric tons of dedicated cargo
Provide airlock for surface activities
Descent stage:
- Liquid oxygen / liquid hydrogen propulsion
Ascent stage:
- Storable propellants
What Makes Constellation Different than Apollo?

We’re going there to stay!
CONSETTLEATION CAN LAND ANYWHERE ON THE MOON

Previous Missions Landed in Equatorial Band

North Pole
Aristarchus Plateau
Rima Bode
Mare Tranquillitatis
Mare Smythii
Oceanus Procellarum

South Pole

Central Farside Highlands
Orientale Basin Floor
South Pole – Aitken Basin Floor

Luna
Surveyor
Apollo
Potential Constellation Landing Sites

Near Side
Far Side
Conceptual NASA Lunar Surface Architecture

- Power & Support Unit (PSU) (Supports power storage, cargo offloading & lander)
- 10 kW Arrays (net)
- ISRU Oxygen Production Plant
- Logistics Pantry
- Habitation Element
- Habitation Element
- Unpressurized Rover
- Small Pressurized Rover (SPR)
- ATHLETE Mobility System (2)
- Common Airlock With Lander
The lunar South Pole is a likely candidate for an outpost site.

Several areas with greater than 80% sunlight and less extreme temperature swings.

Elevated quantities of hydrogen, possibly water ice in permanently shadowed craters.

Step-by-step outpost construction:
- Power system
- Communications/navigation
- Habitat
- Rovers
What is Lunar Mining – Space Resource Utilization?
Uses of Space Resources for Robotic & Human Exploration

Mission Consumable Production
- Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles
- Fuel cell reagents for mobile (rovers, EVA) & stationary backup power
- Life support consumables (oxygen, water, buffer gases)
  - Gases for science equipment, drilling, and cleaning
  - Bio-support products (soil, fertilizers, etc.)
  - Feedstock for in-situ manufacturing & surface construction

Surface Construction
- Radiation shielding for habitat & nuclear reactors from in-situ resources or products (Berms, bricks, plates, water, hydrocarbons, etc.)
- Landing pad clearance, site preparation, roads, etc.
  - Shielding from micro-meteoroid and landing/ascent plume debris
  - Habitat and equipment protection

Manufacturing w/ Space Resources
- Spare parts manufacturing
  - Locally integrated systems & components (especially for increasing resource processing capabilities)
  - High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)

Space Utilities & Power
- Storage & distribution of mission consumables
- Thermal energy storage & use
- Solar energy (PV, concentrators, rectennas)
- Chemical energy (fuel cells, combustion, catalytic reactors, etc.)
Lunar Space Resource Utilization Operation Cycle

Global Resource Identification

Local Resource Exploration/Planning

Mining

Site Preparation

Communication & Autonomy

Site Preparation

Maintenance & Repair

Processing

Crushing/Sizing/Beneficiation

Product & Utilization

Waste
ISRU - Related Surface Elements & Activities

- **Resource & Site Characterization**
- **Regolith Excavation & Sorting**
- **Site Preparation** (roads, pads, berms, etc.)
- **Regolith Transport**
- **Polar Volatile Extraction**
- **Power Source** (Solar Array or Nuclear Reactor)
- **In-Situ Energy Generation & Storage**
- **Regolith Crushing & Processing**
- **Surface Construction**
- **Non-Regolith Resource Processing**
- **Product Storage**
- **Life Support Systems**
- **Mobile Transport of Oxygen**
- **Habitats & Shelters**

**Legend:**
- RED = ISRU Elements under development
- Blue = ISRU Elements not being developed
- Brown = Other Surface Elements
- Orange = Site Prep & Construction
- Light Blue = Oxygen Extraction from Regolith
- Purple = Polar Water Extraction
- Green = Trash Processing
- Pink = In-Situ Manufacturing

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Examples of Lunar Mining & ISRU

Landing Pads, Berm, and Road Construction

Carbothermal Processing with Altair Lander Assets

Excavation & Regolith Processing for O₂ Production

Consumable Depots for Crew & Power
What Are The Challenges?
What Do We Face?

- **Apollo Heritage**
  - Design and operation experience and lessons-learned a based on up to 3 days of lunar surface operation during lunar ‘day’ over 35 years ago
  - Time needed to prepare hardware for launch did not allow lessons-learned from missions to change subsequent mission hardware
  - Lunar simulants used in development were not adequate to prepare for actual operation conditions

- **ISS Heritage**
  - Multiple missions required in specific sequence to build up capability
  - Highly documented and coordinated interfaces required between participants
  - Maintenance, repair, and logistics are critical for long-term operation

- **Issues Facing all Systems for Robotic & Human Lunar Exploration**
  - Lunar Sortie & Outpost hardware needs to:
    - Survive months or years with minimum/no maintenance
    - Operate anywhere on the lunar surface and survive/operate during lunar ‘night’ conditions
    - Operate autonomously/tele-robotically when crew is not present
  - Lunar surface elements from different developers will need to be integrated over time
  - Science or resource prospecting missions into permanently shadowed craters must operate at <100 K for extended periods of time
  - Flight certification testing approach for Shuttle and ISS may not be appropriate
  - Limited or no robotic precursor missions available to gain design and operation experience before deployment
  - No/Limited lunar environment simulation facilities exist today that can handle lunar simulant and all expected environments
Design & Operation Challenges

- **Mass & Power:**
  - Cost of transportation to lunar surface means everything needs to be as low of mass and power as possible

- **Environment:**
  - Lunar conditions: vacuum, 1/6 gravity, solar radiation
  - Extreme temperatures (°), Permanently shadowed craters down to 40 K

- **Regolith:**
  - Extremely abrasive; Extremely dense/packed;
  - Granular material doesn’t flow like on Earth

- **Maintenance:**
  - Must operate for years to be cost effective
  - Astronaut maintenance difficult in vacuum with gloves
  - Minimum spare parts available (logistics)

- **Operation:**
  - Autonomous and tele-operation primarily; 2 second round-trip communication delay with Earth; May not have continuous communication

- **Integration:**
  - Hardware and systems from multiple countries must be compatible with each other to achieve desired capabilities and operations
Lunar Mare Soil

Agglutinate: Pieces of minerals, rocklets, and glass welded together by shock-melt glass

Lunar Soil Formation
Micrometeorites

Solar Wind
Condensation
Vaporization

Comminution, Agglutination, & Vapor Deposition

Impact-Glass Bead
Volcanic Glass Bead

Rock Chips

Impact Glass

Regolith: broken up rock material
Soil: <1 cm portion of the Regolith
Dust: <50 μm portion of the Soil

The bulk of lunar soil is <1 mm in size

Courtesy Dr. Larry Taylor, Univ. of Tennessee

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Lunar Soil Characteristics

The bulk of lunar soil is <1 mm in size

Particle Size Distribution

Particle Weight Distribution

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>Mean Size, $M_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>&lt;1 cm</td>
</tr>
<tr>
<td>(weights in grams)</td>
<td>(mm)</td>
</tr>
<tr>
<td>14163</td>
<td>0.0</td>
</tr>
<tr>
<td>15220</td>
<td>0.0</td>
</tr>
<tr>
<td>68500</td>
<td>1.3</td>
</tr>
<tr>
<td>72140</td>
<td>1.3</td>
</tr>
<tr>
<td>72500</td>
<td>3.1</td>
</tr>
<tr>
<td>73240</td>
<td>1.6</td>
</tr>
<tr>
<td>74220*</td>
<td>0.0</td>
</tr>
<tr>
<td>78220</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Distribution of particle sizes in separate splits of Apollo 17 soil 78221,8,

Weight distribution in size fractions of scooped surface soils.

Courtesy Dr. Larry Taylor, Univ. of Tennessee

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**Lunar Soil Properties**

**Specific Gravity:** Range from 2.3 to >3.2; recommend 3.1 for Engineering use.

**Bulk Density:**
- Top 15 cm = 1.45-1.55 g/cm³; avg = 1.50 ±0.05 g/cm³
- 0-30 cm = 1.53-1.63 g/cm³; avg = 1.58 ±0.05 g/cm³
- 30-60 cm = 1.69-1.79 g/cm³; avg = 1.74 ±0.05 g/cm³
- 0-60 cm = 1.61-1.71 ±0.05 g/cm³; avg = 1.66 ±0.05 g/cm³
  - Values up to 1.9 g/cm³ estimated at depth of cores to 2.98 m

**Slope Stability**

Calculated stability of artificial slopes constructed in lunar surface material.

Data are presented for 3 situations:

1. An excavation in lunar soil
2. A compacted pile of excavated lunar soil
3. A dumped pile of lunar soil

A vertical cut can safely be made in lunar soil to a depth of about 3 m; an excavated slope of 60° can be maintained to a depth of about 10 m.

**Soil Porosity**

<table>
<thead>
<tr>
<th>Depth Range (cm)</th>
<th>Average Porosity n, (%)</th>
<th>Average Void Ratio, e</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>52 ± 2</td>
<td>1.07 ± 0.07</td>
</tr>
<tr>
<td>0-30</td>
<td>49 ± 2</td>
<td>0.96 ± 0.07</td>
</tr>
<tr>
<td>30-60</td>
<td>44 ± 2</td>
<td>0.78 ± 0.07</td>
</tr>
<tr>
<td>0-60</td>
<td>46 ± 2</td>
<td>0.87 ± 0.07</td>
</tr>
</tbody>
</table>

*Lunar soil, in-situ, is very dense, more than that which could be produced with mechanical compaction equipment*

– the lunar soil has experienced slow shaking over eons of time.

Courtesy Dr. Larry Taylor, Univ. of Tennessee
Examples of Hardware and Operation Challenges

- Low-energy/low-wear regolith movement from hopper to top of reactor
- Zero-leakage valving for regolith inlet/outlet feed
- Gas contaminant removal/clean-up (H₂S, HCl, HF, etc.)
- Internal regolith mixing, heating, and sintering prevention
- Regolith heat recovery from spent regolith to new incoming regolith
- Autonomous control of operations
- Level area clearing hardware
- Post-leveling surface stabilization/hardening
What is NASA Doing?
Lunar Space Resource Utilization Operation Cycle

Global Resource Identification

Local Resource Exploration/Planning

Communication & Autonomy

Site Preparation

Maintenance & Repair

Processing

Crushing/Sizing/Beneficiation

Product & Utilization

Waste

Developing all Steps in the Cycle
Resource Assessment Approach

**Utilize Orbital Assets to Map Lunar Surface Terrain and Resources**
- Lunar Reconnaissance Orbiter & LCROSS

**Utilize Instruments on Rovers and Landers - Tie to Science Objectives**
- Mineral distribution, especially iron-bearing, within 500 m of Outpost
- Physical characterization; size & shape, rock, glass, and agglutinate content, bulk density, thermal capacity and conductivity, force required to penetrate/dig
- Solar wind volatiles: type, amount, energy required to release
- Permanently shadowed crater resources, esp. hydrogen-bearing, and physical characteristics
- Contaminants released during oxygen extraction processing

**RESOLVE incorporates five subsystems from three NASA institutions**
- Drill and sample handling from Northern Centre for Advanced Technology (NORCAT)
- Significant university and Lunar science expertise

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Mobile Resource Characterization & Oxygen Production Demonstration Hardware

- TriDAR Navigation & Drill Site Selection Sensor (Neptec)
- Advanced Stirling Radioisotope Generator Simulator (GRC)
- Scarab Rover (CMU – HRS)
- RESOLVE Drill & Sample Transfer (NORCAT)

RESOLVE Processing Module
- Gas Chromatograph
- Water Capacitance Beds
- Hydrogen Tank
- Neon Tank
- Reactor & Valving

Combined Sample Metering & Crusher Unit
- RESOLVE Fluid System Integration
- RESOLVE Reactor

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Lunar Mining & Site Preparation Needs

- **Excavation for Oxygen Production**
  - Only need to excavate top loosely consolidated regolith (<8 cm deep)
  - For 2 Mt/yr O₂ production with least efficient H₂ Reduction Process
    - > 4% of Chariot time required or
    - > 30% of 2 mini-rovers (250 kg each)
  - Options include dedicated vehicle vs part-time usage and integrated excavation-hauler vs separate excavation and hauler vehicles

- **Site Preparation for Outpost: Landing pads, berms, roads**
  - Operations can involve area leveling, rock removal, berm building, road/path clearing, and surface hardening (via sintering or binder)
  - Largest excavation and regolith movement requirement over life of Outpost
  - If landers are not moved, a new pad needs to be prepared every 6 months

- **Operations for Outpost Habitat and Reactor Emplacement**
  - Multiple options for Habitat protection if regolith shielding for radiation or thermal is desired
    - > Excavate ramp and flat area and drive habitat below surface
    - > Cover inflatable bridge/structure with regolith before inflation
  - For nuclear reactor, process depends on excavation vehicle size and method of reactor transport and placement
    - Large vehicle stays outside of hole and uses backhoe
    - Small vehicle excavates ramp/hole and reactor is driven into hole
Examples of Lunar Mining Activities Underway

Excavation for O₂ Extraction

Site Preparation - Area Clearing

Crushing & Beneficiation

Surface Sintering / Hardening

Lunar Simulant Development

OB1 Highland Simulant (NORCAT/UNB)
Lunar Highland (LHT) Simulant (MSFC-USGS)
JSC1a (ORBITEC)

Credit: Dr. Paul Hintze, KSC

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Lunar Processing Consumable Production Needs

**Oxygen (O\(_2\)) Production from Regolith**
- 1 mT/yr production rate for ECLSS/EVA closure
- 0.9 mT/yr to make water for ECLSS/EVA closure with lander propellant scavenging
- 9 to 10 mT/yr production rate during Outpost operation would also support refueling 2 ascent vehicles per year to further increase payload delivery capability
- Options include: Hydrogen reduction (1 to 5% kg O\(_2\)/kg bulk regolith), Methane Carbothermal reduction (10 to 28%), and Molten electrolysis (up to 40%)

**In-Situ Water Production**
- 0.9 MT/yr water needed for life support/EVA closure
- ~3 MT water needed habitat radiation shielding (3 habitats of 1000 kg each)
- ~225 kg water needed for each Small Pressurized Rover thermal/radiation system (2 minimum)

  Note: Recent architecture evaluations require more water than stated above
  - Options include:
    - **Double amount of water produced from propellant scavenging** by adding in-situ oxygen (40 to 60 kg of H\(_2\) remains after all residual O\(_2\) is consumed to make water)
    - Post-ECLSS crew waste/plastic trash processing to complete extraction of water
    - Polar water/ice extraction and processing only needed if large scale in-situ propellant production is used incorporated into the architecture

**In-Situ Methane Production**
- ~2100 kg/yr supports refueling 2 ascent vehicles per year.
- Capability can be used to initially supports LSAM Ascent ‘top-off’ in case of leakage, power loss, or increased payload to orbit before completely refueling ascent vehicle
- Options include:
  - Utilize methane produced by habitat life support system (400-500 kg/yr for crew of 4)
  - Process plastic trash and crew waste with in-situ oxygen to make methane
Lunar Processing – Oxygen & Metal Extraction

**Hydrogen Reduction of Regolith**

1. Heat Regolith to >900 °C
2. React with Hydrogen to Make Water
3. Crack Water to Make O₂

\[ \text{FeO} + \text{H}_2 \rightarrow \text{Fe} + \text{H}_2\text{O}; \quad 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]

- Two Fluidized H₂ Reduction Reactors - 10 kg/batch each (1050 °C)
- Regolith hopper/auger lift system (2)
- Water Electrolysis Module
- O₂ Cryo Tank
- Hydrogen Storage
- PILOT 250 kg O₂ per year
- Lift System and Auger Loading
- Bucket Drum Excavator (IR&D)
- Dump Chute

**Carbothermal Reduction of Regolith**

1. Melt Regolith to >1600 °C
2. React with Methane to CO
3. Convert CO to Methane & Water
4. Crack Water to Make O₂

\[ \text{SiO}_4 + \text{CH}_4 \rightarrow \text{CO} + 2\text{H}_2 + \text{Si}; \quad \rightarrow \quad \text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}; \quad 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]

- Lift System and Auger Loading
- Regolith Storage – 1 day
- Regolith Reduction Chamber

**Molten Electrolysis of Regolith**

1. Melt Regolith to >1600 °C
2. Apply Voltage to Electrodes To Release Oxygen
1st Generation of Lunar Mining & Processing Equipment Built and Tested

ISRU Systems Field Tested in Hawaii, Nov. 2008
3 Major Systems Tested for First Time

RESOLVE: Resource Prospector and O₂ Demonstration System

JSC “ROxygen” System

Lockheed Martin O₂ System: PILOT
Next System Field Test in Planning

Advanced Lunar ISRU Cycle Hardware & Operations

Site & Resource Exploration
- NORCAT/CSA Platform
- GPR & RESOLVE Drill for subsurface validation
- Hand-held and rover mounted CSA & NASA MMAMA Instruments

Site Preparation & Excavation
- Autonomous and Tele-operation Area
- Clearing/Excavation Implement Testing
- NORCAT/CSA Platforms
- Surface Sintering

Solar Energy
- Upgraded GRC Solar Array Cart
- (Power Project Involvement)
- Upgraded JSC ROxygen Water Electrolysis
- Solar Concentrator
- Solar Energy

Mining & Processing
- NORCAT/CSA Platform
- Tele-operated & Autonomous Excavation and Delivery
- Carbothermal Reduction Reactor
- Upgraded JSC ROxygen Water Electrolysis
- H₂O
- H₂
- O₂

Product & Utilization
- O₂ Liquefaction and Storage
  (CFM Project Involvement)
- CSA Fuel Cell – Hydride Tank Resupply
- H₂ Storage & Transfer
Long-Term Plans to Link Lunar Surface Elements Together

**Moses Lake, WA – 6/08**
- Crew & Tele-operation Non-articulating Area Clearing/Berm Building

**Blackpoint Lava, AZ – 9/09**
- Crew & Tele-operation Articulating Area Clearing/Berm Building on SPR
- Fuel Cell w GO2/GH2 Storage, Transfer, & Resupply

**Desert RATS – 9/10**
- Fuel Cell w LO2/GH2 Storage, Transfer, & Resupply

**Mauna Kea, HI – 11/08**
- Local Tele-operation Excavation for O2 Production

**Mauna Kea, HI – 1/10**
- CSA-NASA Local and Remote Tele-operation and Autonomous Site Preparation & Excavation
- Solar Surface Sintering

**Mauna Kea, HI – 1/11?**
- Remote Tele-operation and Autonomous Site Excavation for O2 Production – Surface Stabilization for Rocket Engine Firing

1st Gen H2 Reduction – Separate Water Electrolysis – Gaseous O2 Storage – Gas Generator Power

2nd Gen H2 Reduction – Integrated Water Electrolysis – Liquid O2 Storage, Transfer, and Propulsion

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