08-461

Oxygen and Metals Processing on the Moon:

Will Materials Science Change our future in space?

Laurent Sibille, ASRC Aerospace

Donald R. Sadoway, MIT

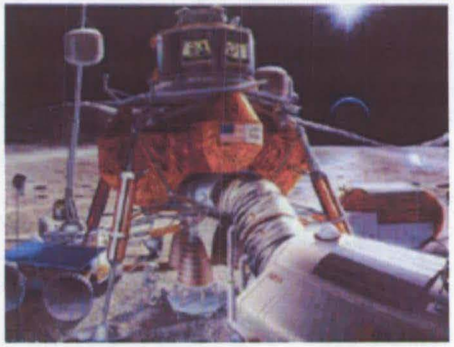
ISRU: Decisions from Lunar Architecture Development

- ISRU is a critical capability and key implementation of the VSE and sustained human exploration

- At the same time, ISRU on the Moon is an unproven capability for human lunar exploration and can not be put in the critical path of architecture until proven

- Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired endstate

- Architecture is designed to be open enough to take advantage of ISRU from whatever source when available



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

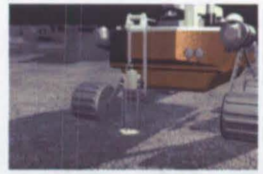
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

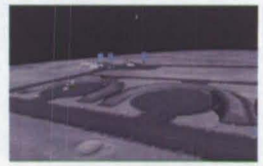
In-Situ Lunar Resources

- **'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, material, etc. after landing
  - Crew trash and waste (after Life Support processing is complete)

Lunar ISRU Products and Services

- **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
- **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)
- **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)





Three Pronged Approach to ISRU Development & Incorporation

- **Identify how ISRU fits into Architecture for Sustained human presence on the Moon**
  - Non-critical path initially with fall back strategy
  - Evolutionary with growth in:
    - Capability
    - Criticality
    - Ties to Mars
    - Ties to Space Commercialization
- **Build confidence in ISRU early and often**
  - Multiple generations of hardware and systems developed
  - Extensive ground and analog site testing for operations, maintenance, and interconnectivity
  - Robotic precursors if possible to reduce risk AND
    - Tie to common science objectives for regolith, mineral, and volatile characterization
    - Tie to long-term operations associated with Outpost deployment and operation
- **Early NASA involvement in all aspects of ISRU with transition to industry**
  - Ensures NASA is 'smart' buyer
  - Ensures lessons learned from ground and flight demonstrations are transferred to all of industry (unless pre-agreement established for commercialization aspect)
  - Ensures long-term industry involvement for spin-in and spin-off applications

ISRU Consumable Production for Lunar Architecture

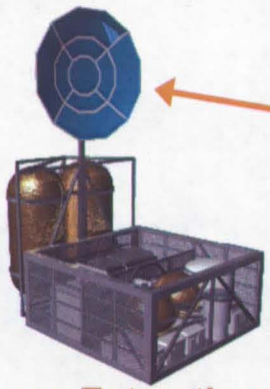
- **O_2 Production from Regolith**
  - –2 MT/yr production rate for surface mission consumables – 1 MT/yr for ECLSS/EVA and 1 MT/yr to make water
  - –Capability manifested on 6th landed mission (before start of permanent presence)
  - –Increased production to 10 MT/yr during Outpost operation could also support refueling 2 ascent vehicles per year to further increase payload delivery capability
- **In-Situ Water Production**
  - –Scavenge minimum of 55 kg of hydrogen (max. ~252 kg) from each LSAM descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water
  - –Polar water extraction not evaluated in Lunar Architecture Phase II effort. Not needed unless large scale in-situ propellant (O_2 & H_2) production is required
- **In-Situ Methane Production**
  - –Pyrolysis processing of plastic trash and crew waste with in-situ oxygen can make methane
  - –Capability supports LSAM Ascent 'top-off' in case of leakage, power loss, or increased payload to orbit

ISRU Processing Requirements	kg/yr (min.)
Oxygen Production	
For ECLSS & EVA	1000
For Water Production	800
For LSAM Ascent Propulsion	7600
Water Production	
For ECLSS & EVA (from in-situ O_2 + Scavenged H_2)	900
Required H_2 Scavenged from LSAM Descent Stage	100
For radiation shielding (*one time production need)	1000 to 2000*
Water Electrolysis	
For ISRU	1125
For Night time Power	7335
For Pressurized Rover Power (45 kg/mission)**	1260
Methane Production	
For LSAM Ascent Propulsion (max)	2160

** 28 excursions per year with at least 1 MPU

Lunar Architecture ISRU Systems & Technologies

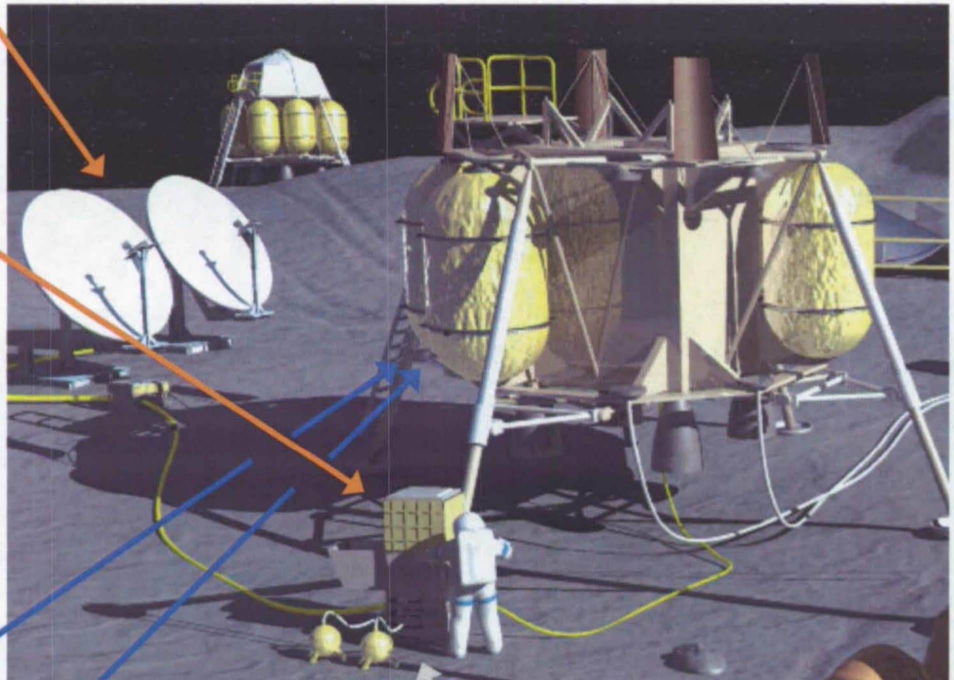
Solar Concentrators
- Lightweight or inflatable collectors
- Thermal management



Oxygen Extraction from Regolith
- Solid/gas processors
- Water electrolysis
- CO_2/methane processors & reagent regeneration
- Contaminant removal
- Thermal management & Radiators
- Dust tolerant sealing

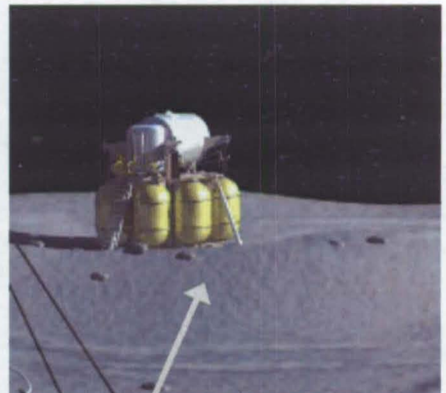
H_2 Scavenging to Make Water
- Dust tolerant O_2 disconnects
- Dust tolerant H_2 disconnects

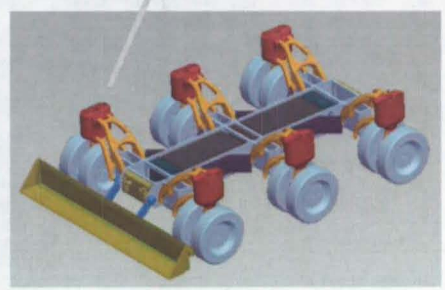
Oxygen Storage-Transfer
- High pressure O_2
- O_2 cryocoolers
- Liquid O_2 storage
- Thermal management
- Dust tolerant O_2 disconnects



Regolith Excavators/Haulers
- Surface mobility platforms
- High-cycle life, high-power density power systems
- End-effectors w/ dust tolerant mechanisms
- Autonomous control

Site Preparation, Berm Building, & Reactor Burial
- Surface Mobility
- High-cycle life, high-power density power systems
- End effectors w/ dust tolerant mechanisms
- Autonomous control





Small vs Large Rovers

ISRU System & Surface Operations Ground Demo Plan

2007	2008	2009	2010	2011

Site Preparation & Outpost Deployment

Inflatable Shelter concept

Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation

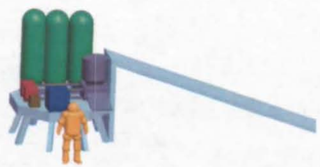
(At JSC)

Perform area clearing and berm building with Chassis C & ISRU Blade

(At JSC & Hawaii)

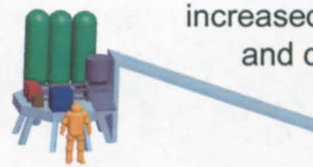
Add Autonomy & increased capabilities (ex. dig hole for reactor)

Oxygen Extraction from Regolith



Excavation and oxygen production from regolith with H_2 Reduction at 250 kg to 1000 kg per year rate for 1 to 5 days

(At Meteor Crater)



Add Autonomy & increased capabilities and durations

Excavation and oxygen production from regolith using carbothermal reduction at 250 to 1000 kg per year with solar power

(At Meteor Crater or Hawaii if in-situ material can be used)

ISRU Precursor & Site/Resource Characterization

Integrate RESOLVE drill on CMU rover

(At CMU)

Integrate complete RESOLVE package on CMU rover

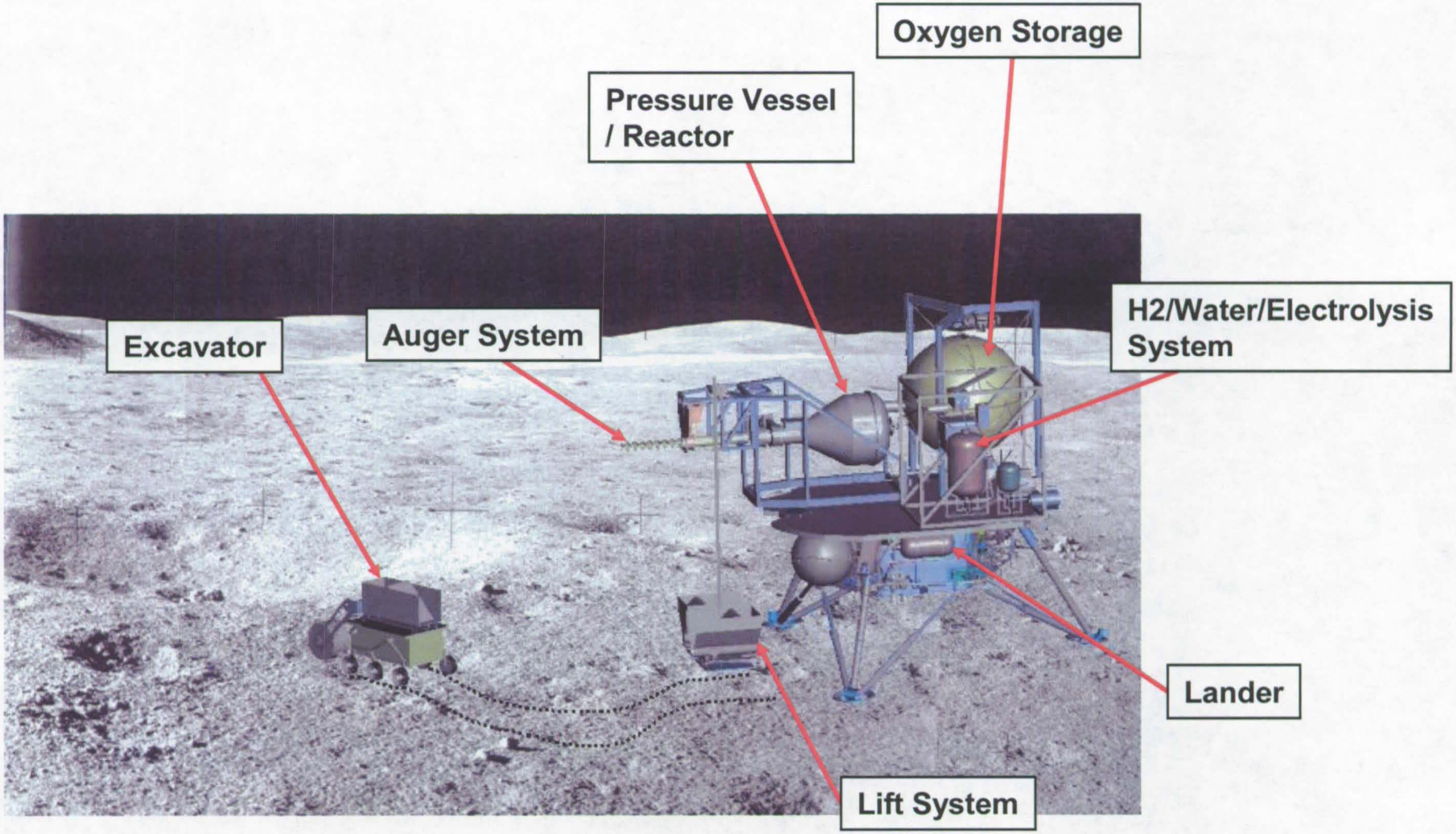
(At Hawaii- permafrost)

Possible:

1. Add Advanced Power system to Rover
2. Perform joint demo with ARC K-10 rovers

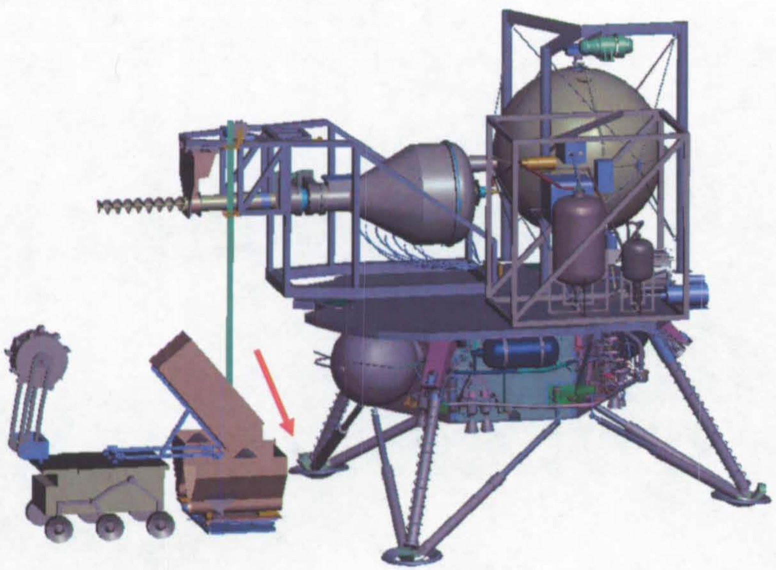
Notional: Integrate other science instruments for prospecting on single platform (ex. GPR, Neutron Spec. etc.)

LMA PILOT Baseline System

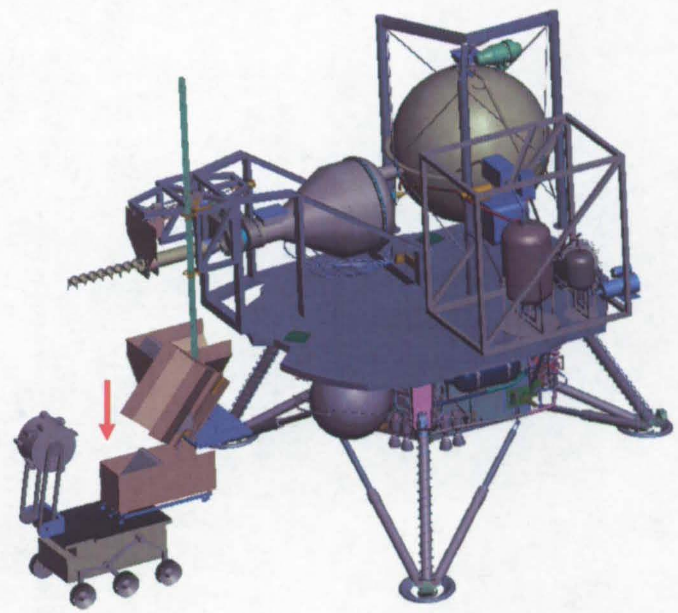


Rover/Lift System Interface

- Rover returns from excavation site and delivers fresh regolith to lift system
- Lift system dumps previous batch's spent regolith into rover bed
- Lift systems hoists fresh material up to auger as rover heads off to dump and dig next batch



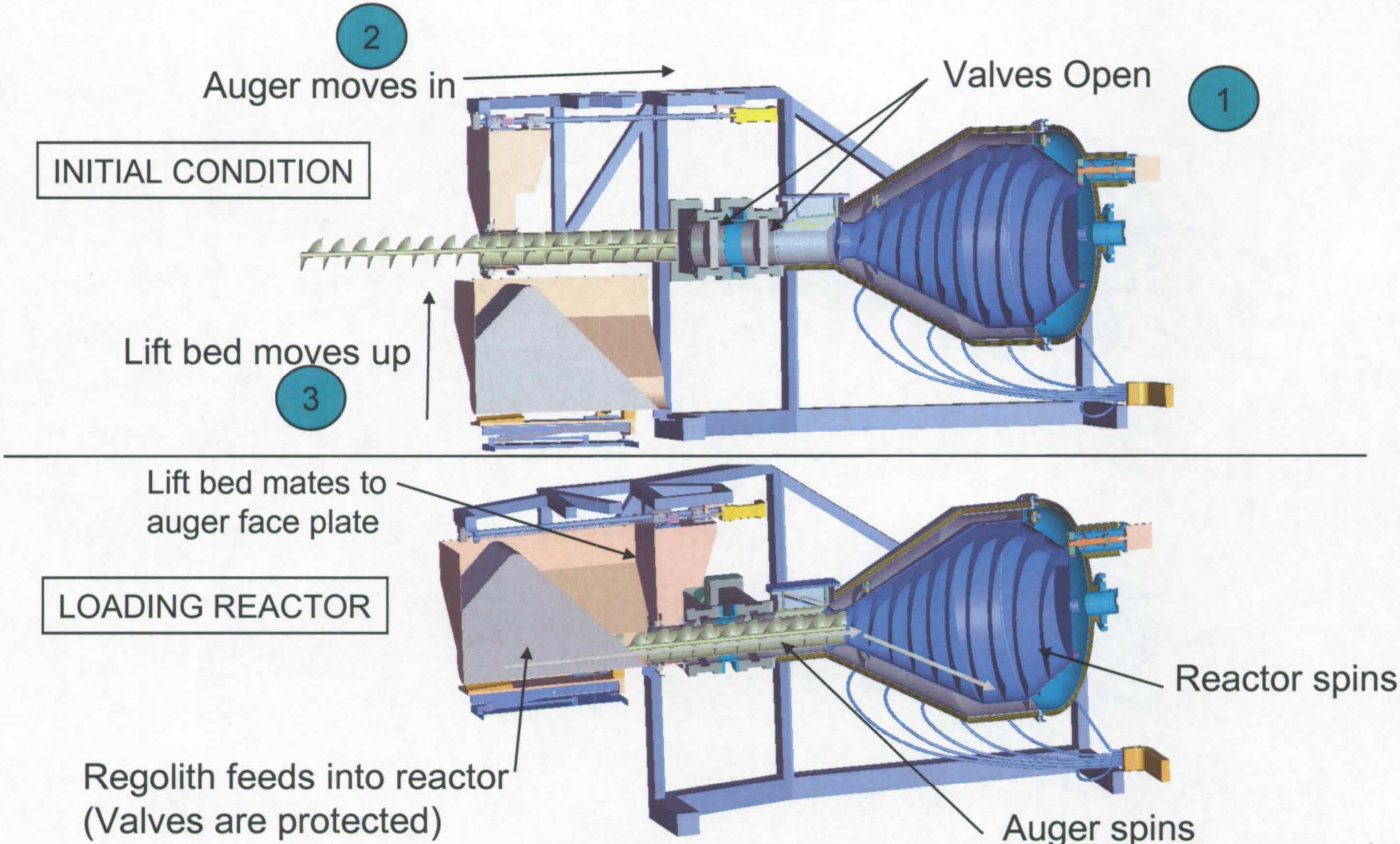
Delivery of fresh material



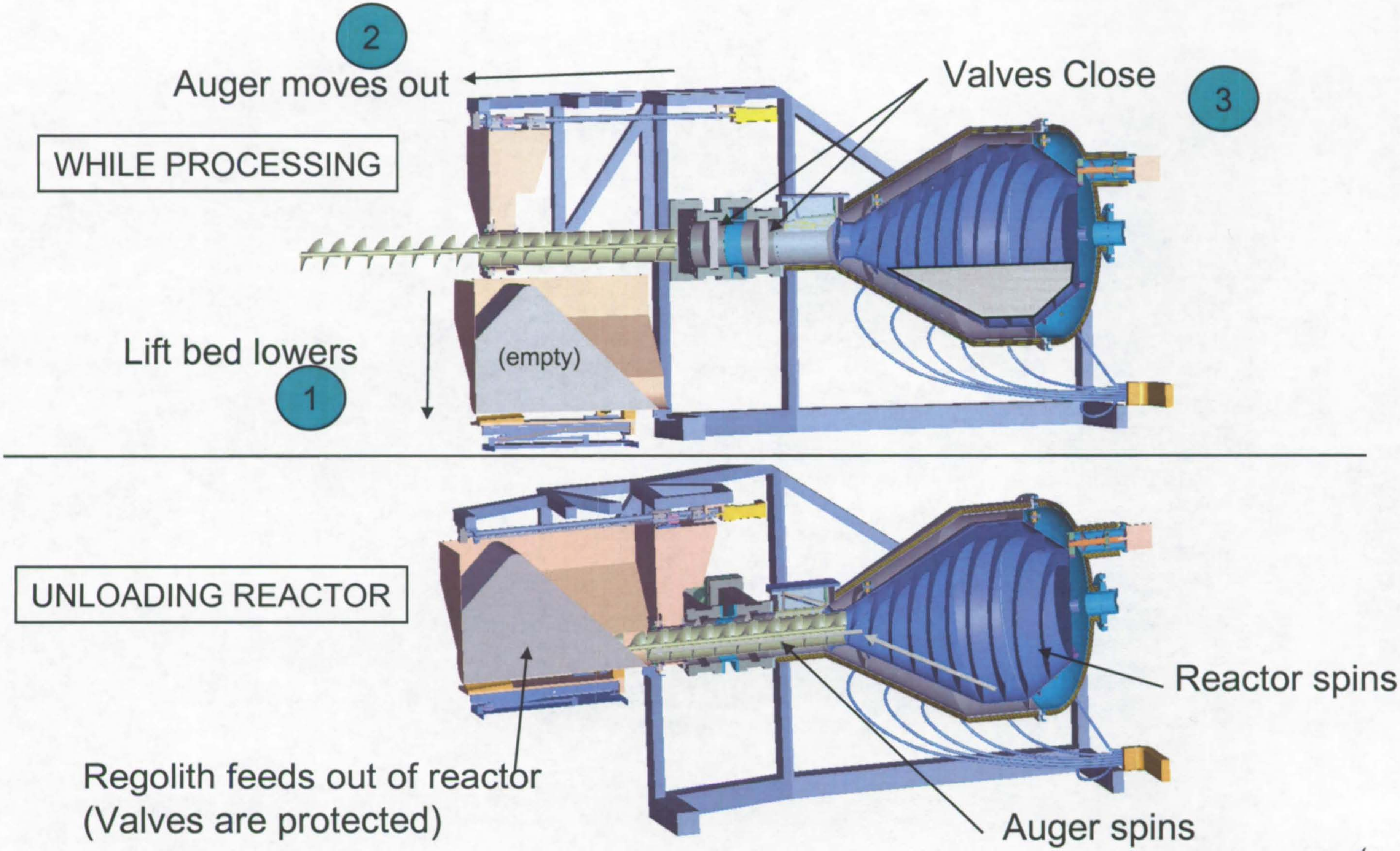
Collection of spent material

LOCKHEED MARTIN

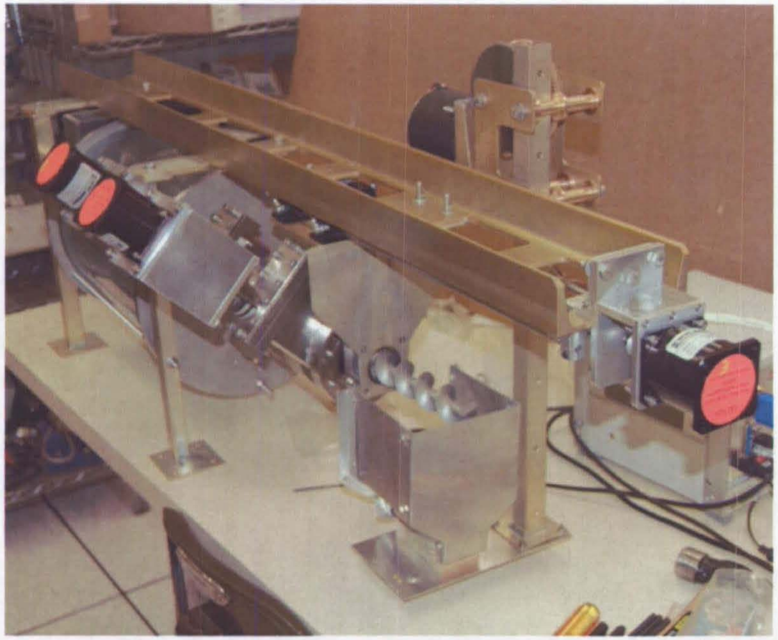
Auger/Reactor Interface



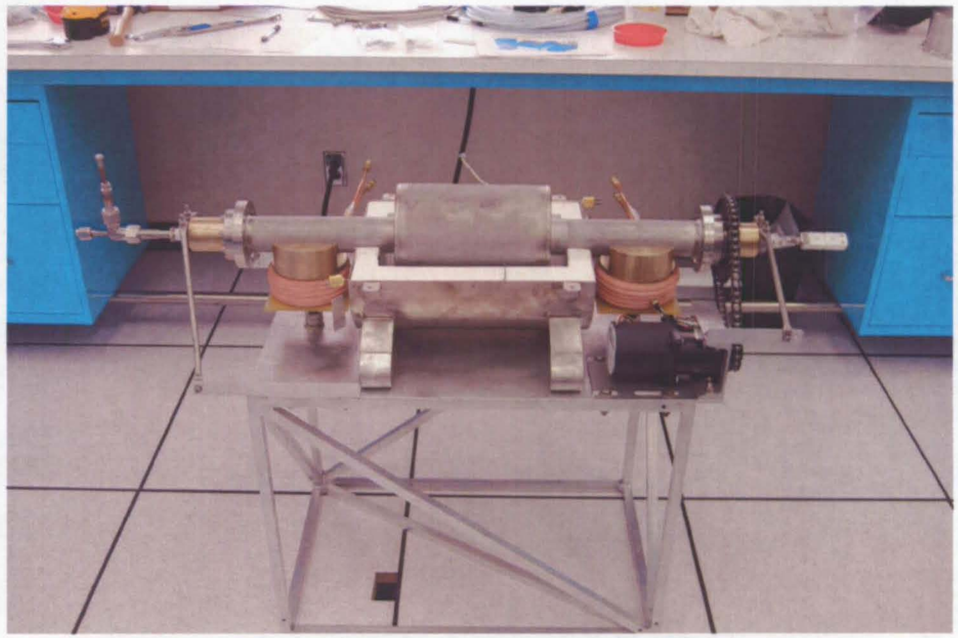
Auger/Reactor Interface



PILOT Hardware



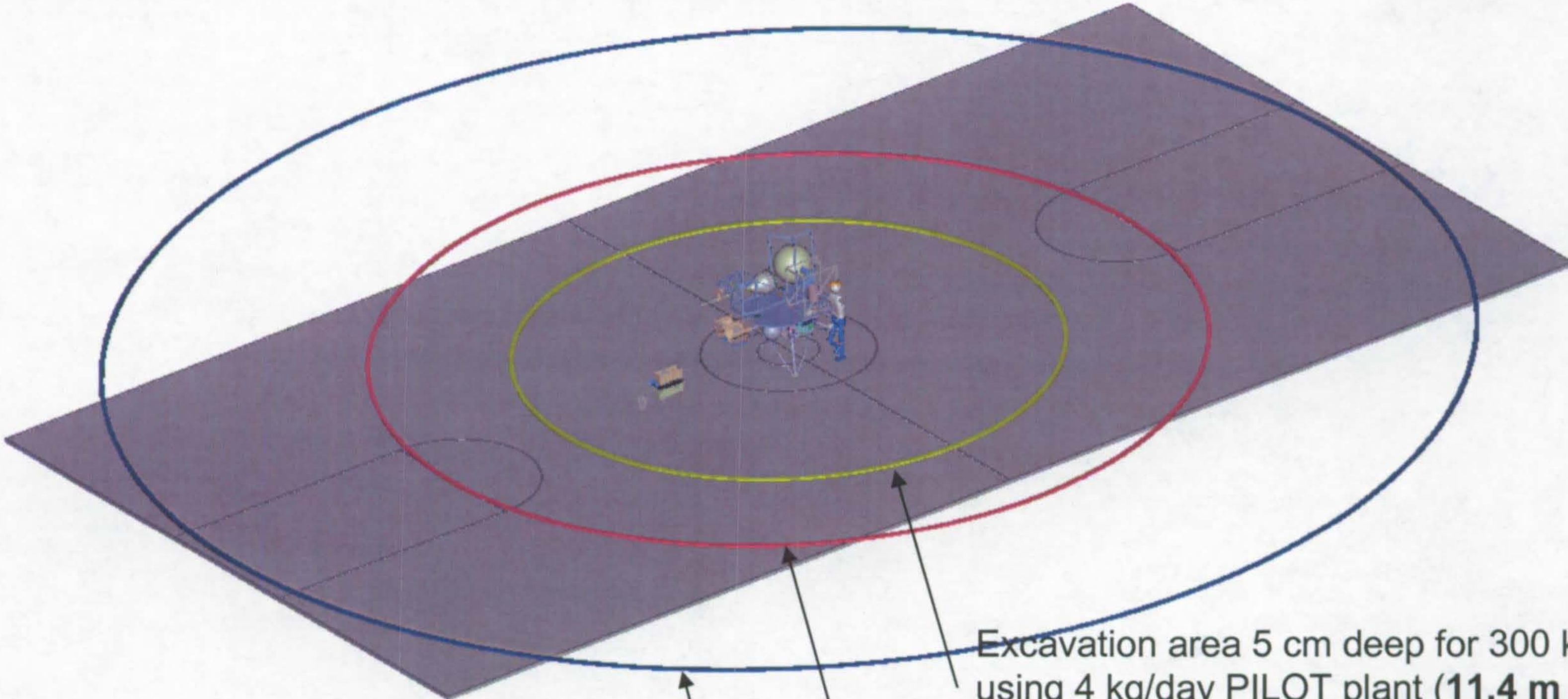
Regolith Handling Test



Hydrogen Reduction Reactor

Photos Courtesy of Lockheed Martin Astronautics

Excavation Areas



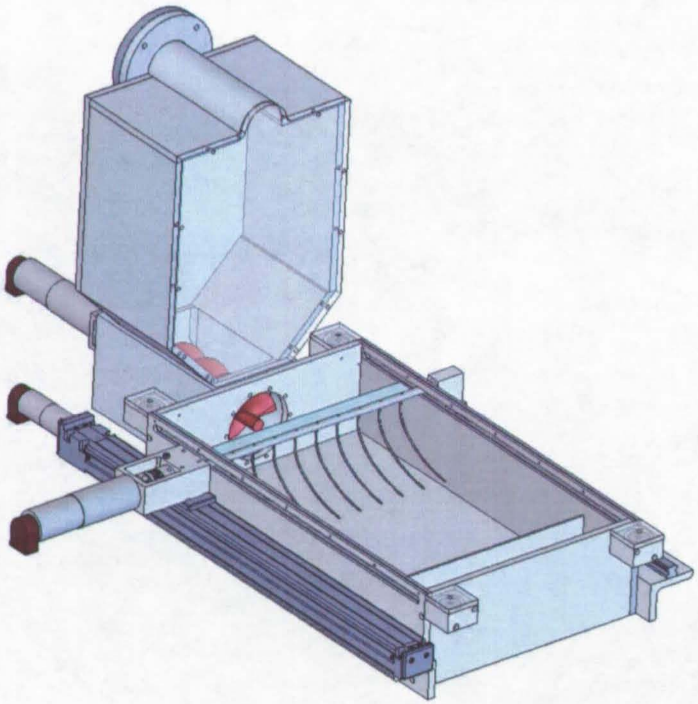
Excavation area 5 cm deep for 300 kg O2 using 4 kg/day PILOT plant (**11.4 m dia circle** or 10m x 10m square) = 7,500 kg regolith excavated

Excavation area 5 cm deep for 730 kg O2 (1 year) using 4 kg/day PILOT plant (**17.3 m dia circle** or 15m x 15m square) = 18,250 kg regolith excavated

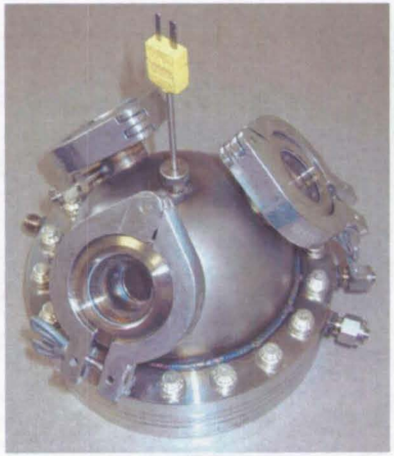
Excavation area 5 cm deep for 2000 kg O2 using 2 mt/yr plant (**28.2 m dia circle** or 25m x 25m square) = 50,005 kg regolith excavated

Areas assume a 4% yield O2 from regolith

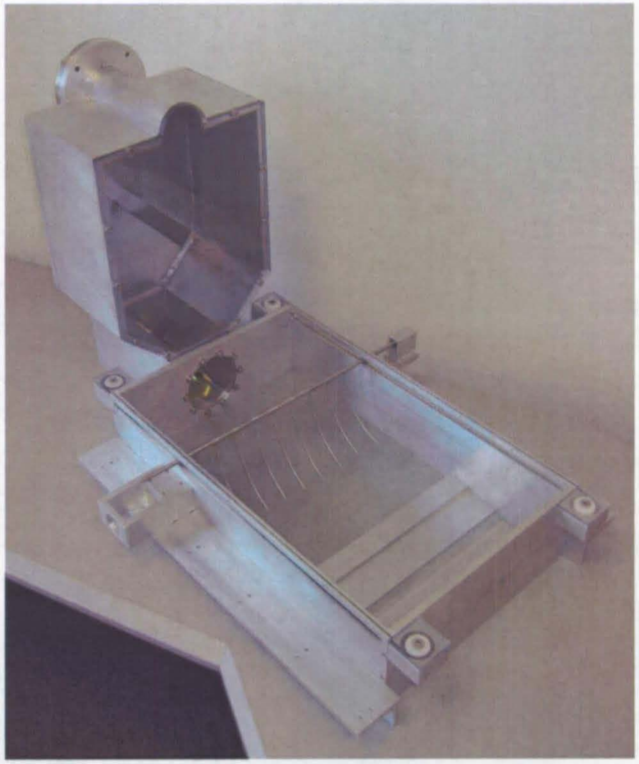
PILOT
Carbothermal Reactor (Orbitec)



Regolith Handling Model



Carbothermal Reactor



Regolith Handling Prototype

Photo Courtesy of Orbitec

Oxygen and Metals Processing on the Moon (PART II):

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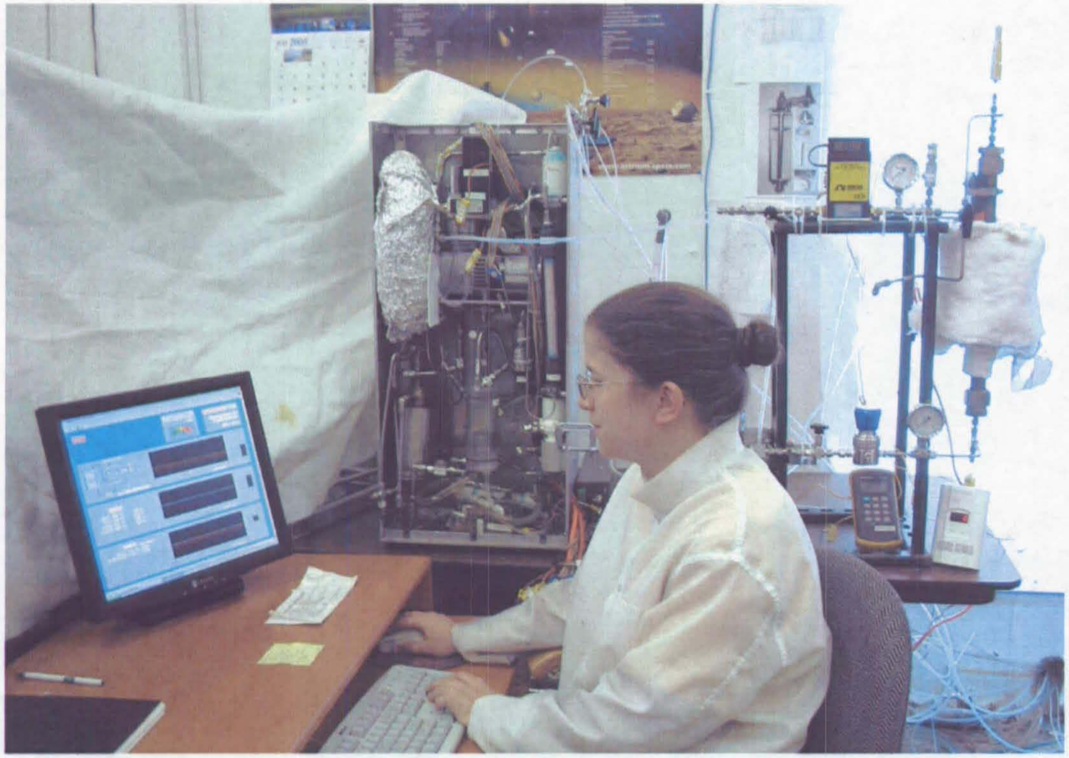
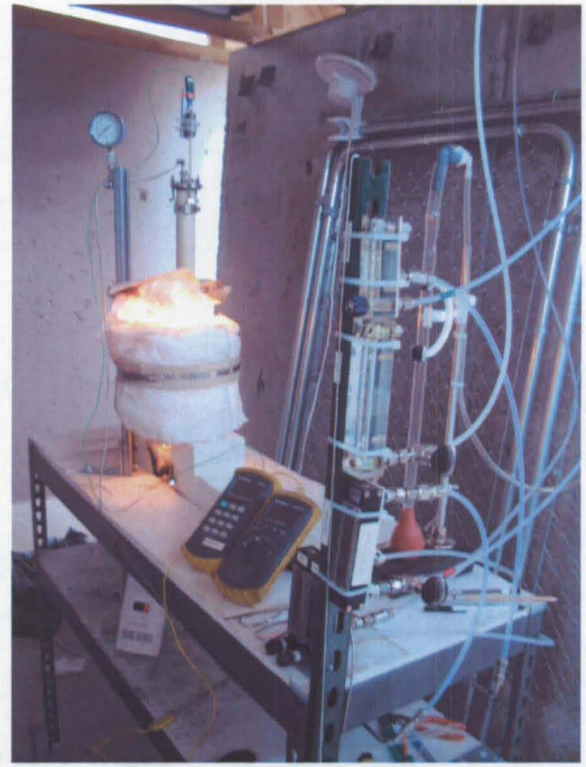
COSRS

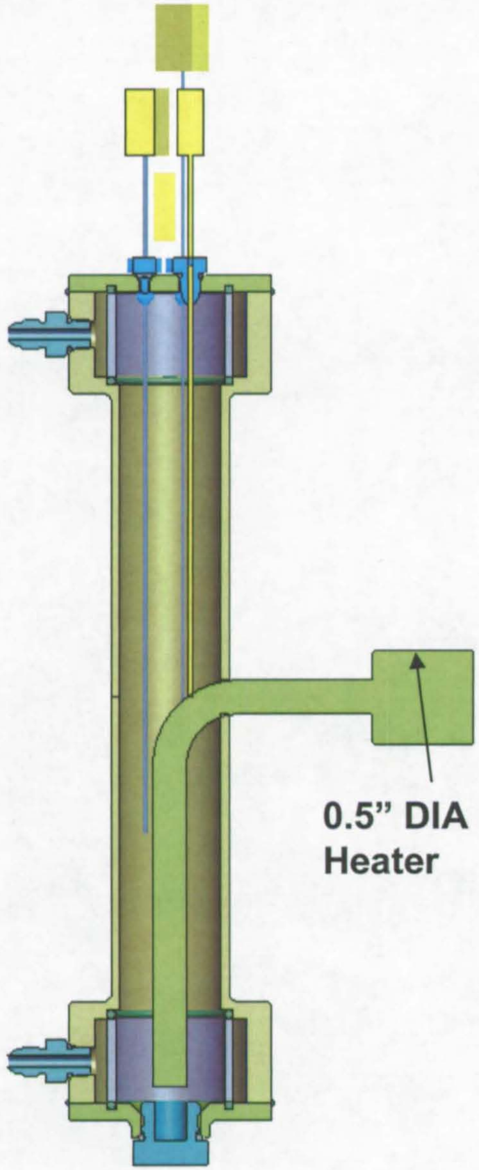
Carbon Monoxide Silicate Reduction System



Integrated COSRS-RWGS-Electrolyzer System During Operation.
From left: LabView® display screen, RWGS-Electrolyzer, COSRS Fe Oxide Reduction Reactor System.



Vertical Carbothermal Reduction in Operation.

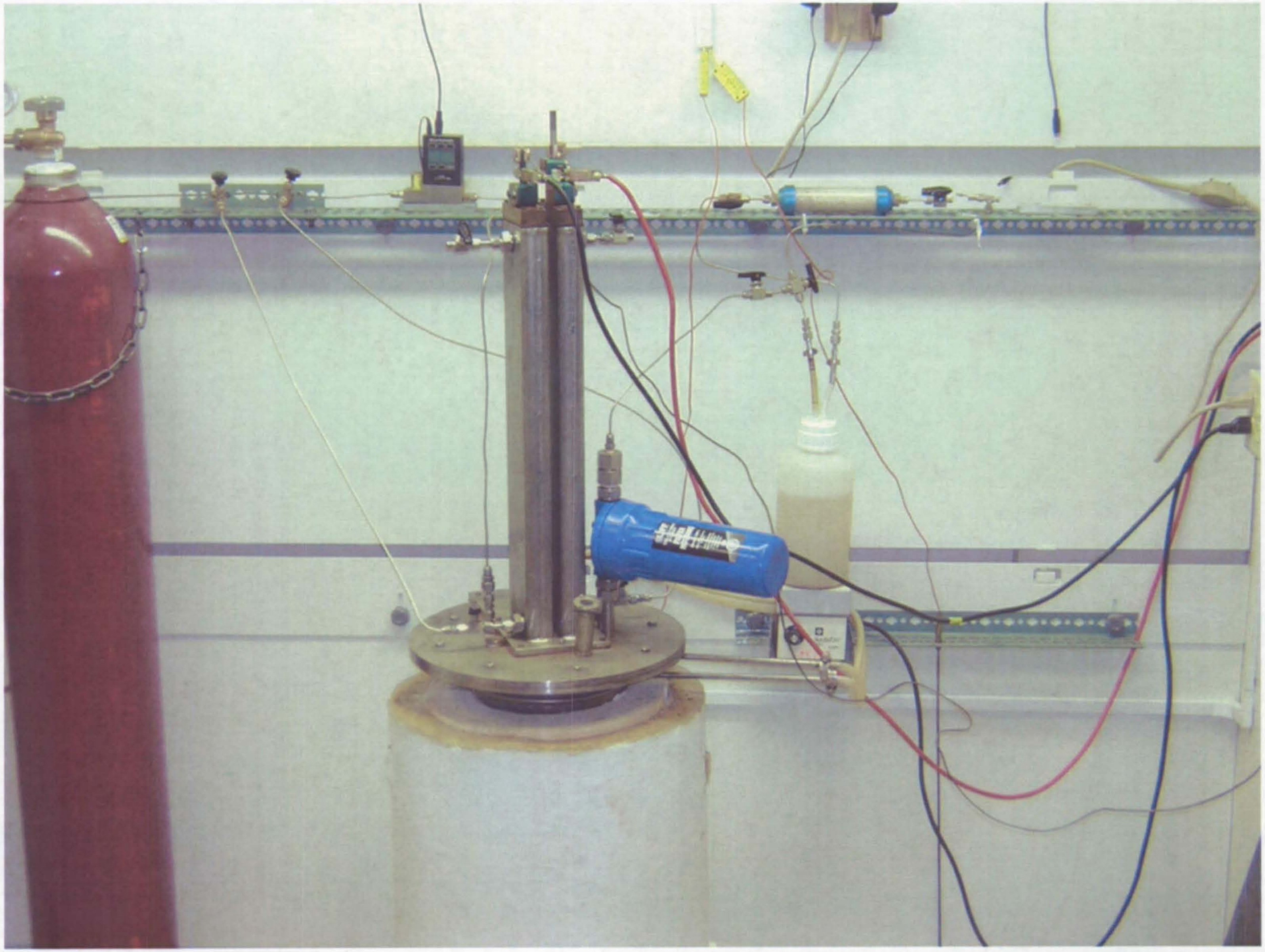


Fluidized Bed Reactor

Reactor Vessel (note pen for scale)

ROX Hardware Under Test

Regolith Electrolysis

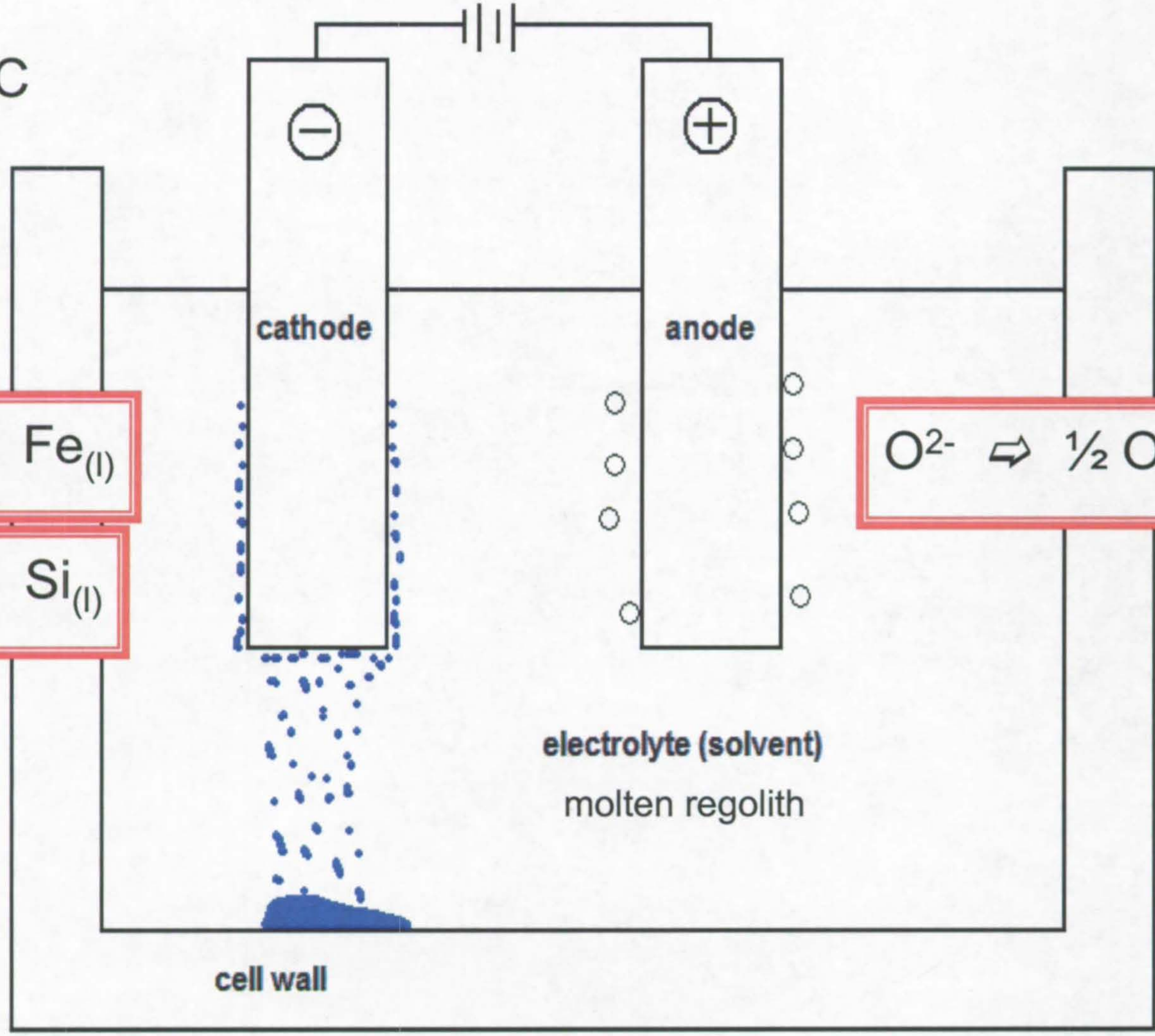


Key O2 System Goals

Key Performance Parameter	State of the Art	Performance Target (full success)	Performance Target (min. success)
Production rate, kg/hr	Not Measured Yet	2.3 kg/hr	1.15kg/hr
Electrical Energy Usage KW/Kg	Not Measured Yet	1.5 KW/Kg	2.0 KW/Kg
Operation Duration, days	Lab Test, 10's to 100's of minutes	1095 earth days	180 earth days
Mean Time Between Repair, days of operation	No Tests to Failure	365 earth days	180 earth days
Reactant Losses	8% to 15%	0.5%	5%

Direct Molten Oxide Electrolysis

T ≈ 1600°C



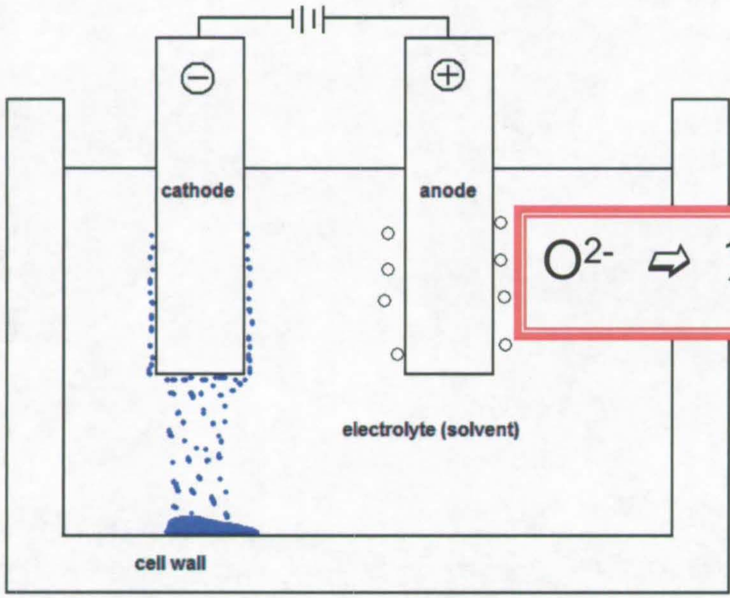
$Fe^{2+} + 2e \Rightarrow Fe_{(l)}$

$Si^{4+} + 4e \Rightarrow Si_{(l)}$

$O^{2-} \Rightarrow \frac{1}{2} O_{2(g)} + 2e$

Direct Molten Oxide Electrolysis

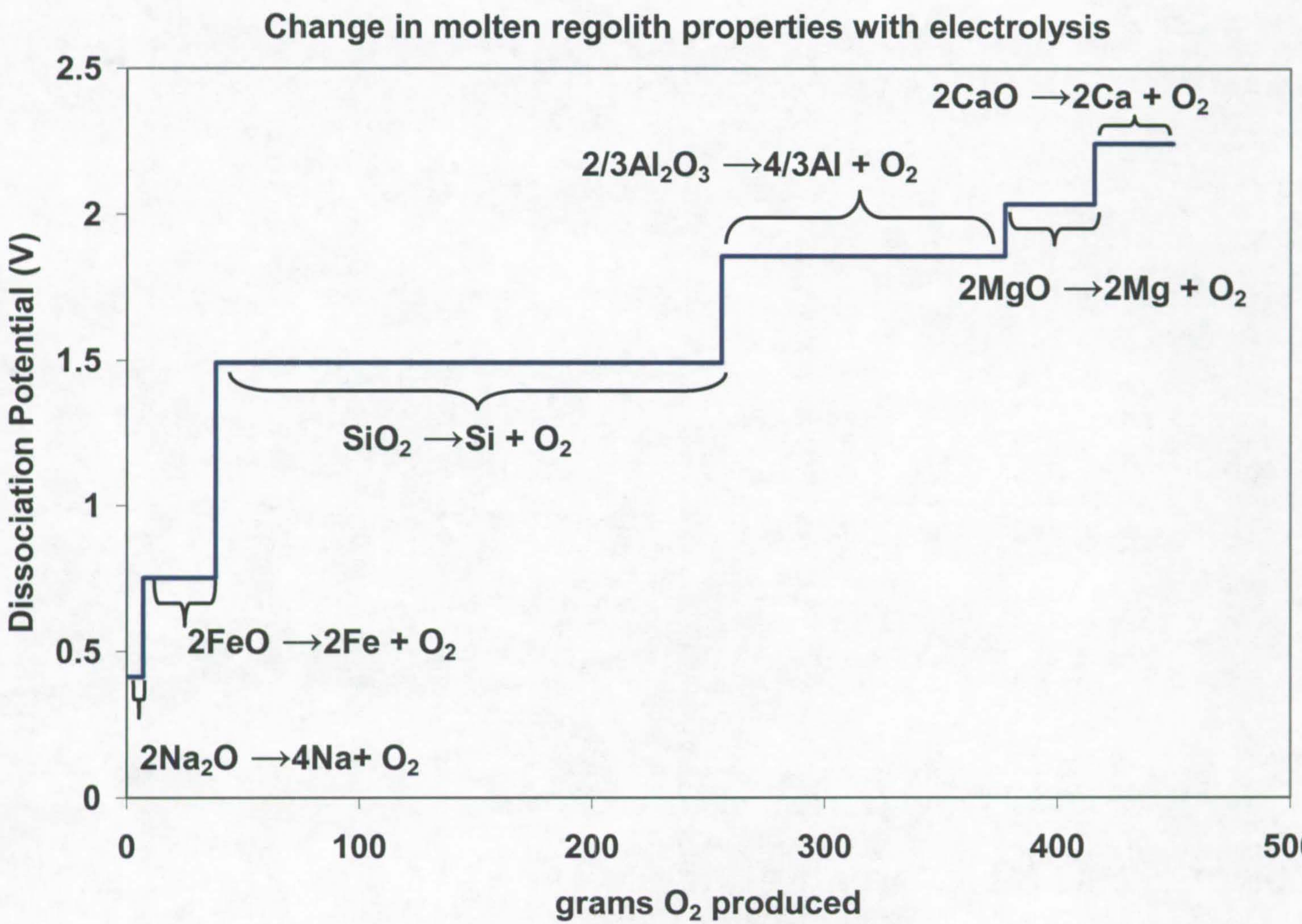
T ≈ 1600°C



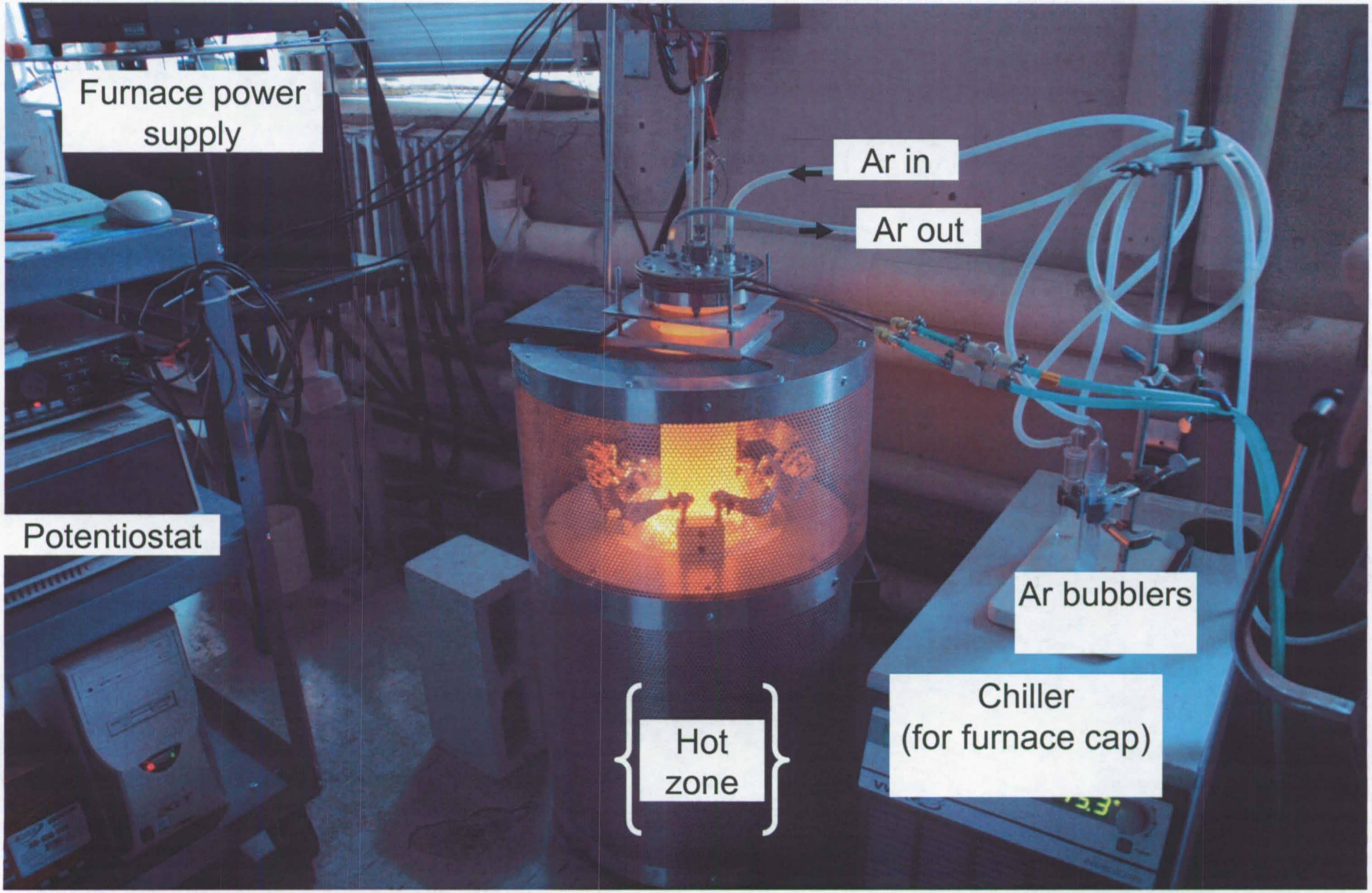
$$O^{2-} \Rightarrow \frac{1}{2} O_{2(g)} + 2e$$

- **Goals of direct electrolysis of molten silicates.**
  - determine most active anode catalyst for OER.
  - find inert (non consumable) anode.
  - determine current density, voltage and power requirements for scale up.
  - quantitative and qualitative analysis of oxygen

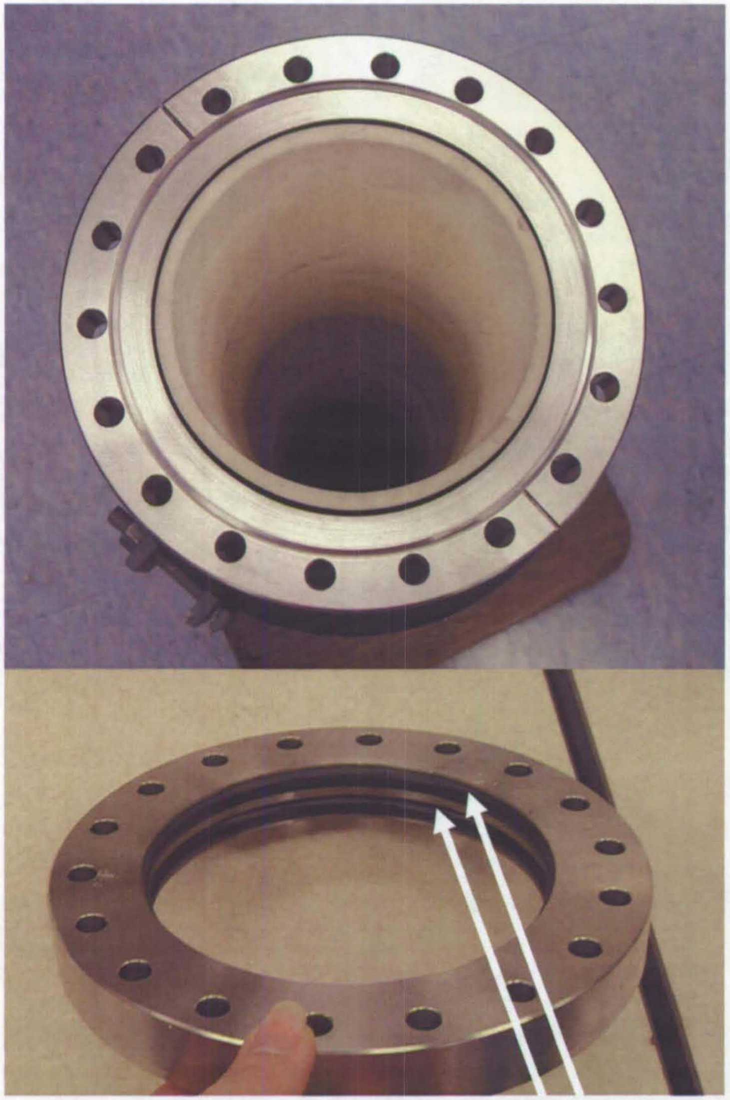
Relative amounts of regolith constituents and energy cost associated with electrowinning of each



Electrolysis Cell Setup

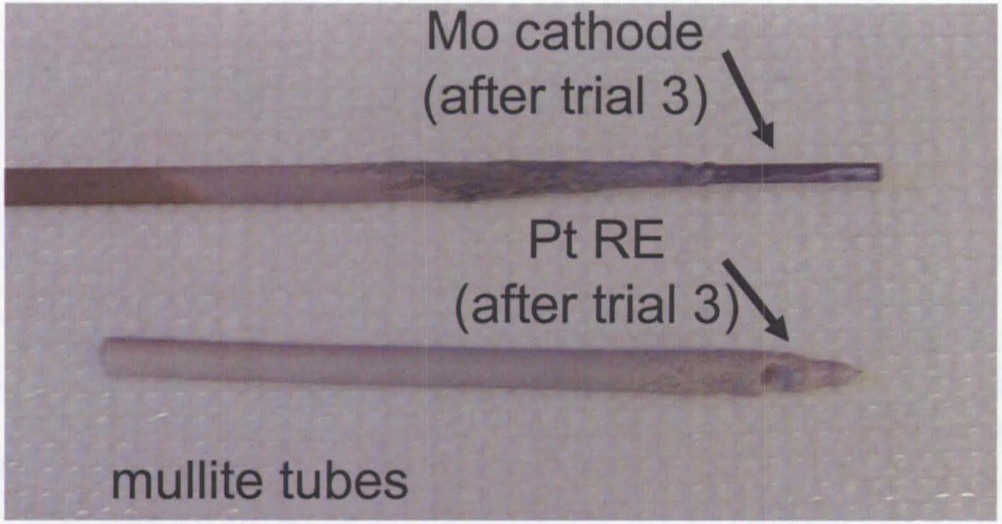


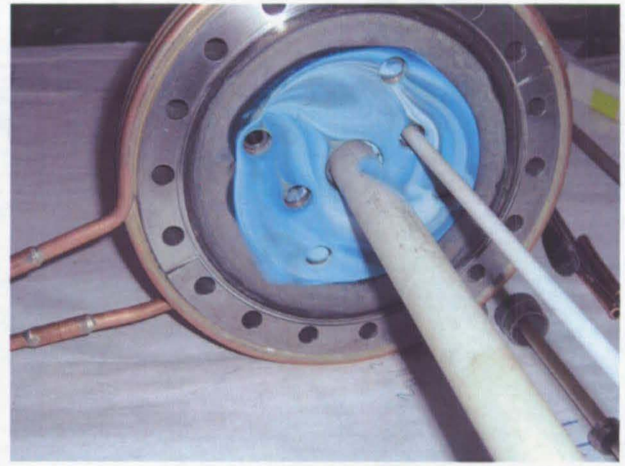
Redesigning cell cap for oxygen capture

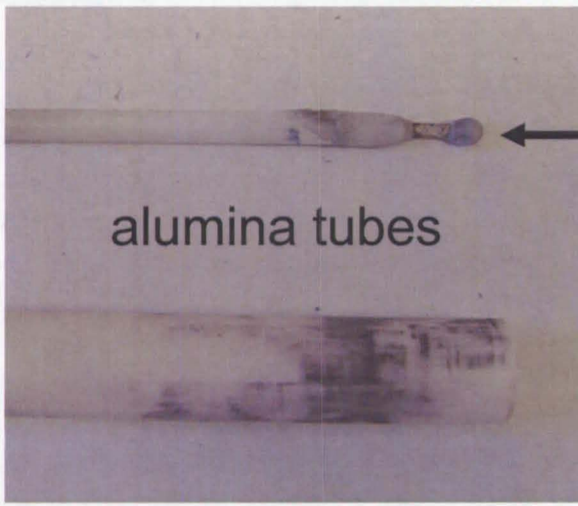


Double o-ring seal

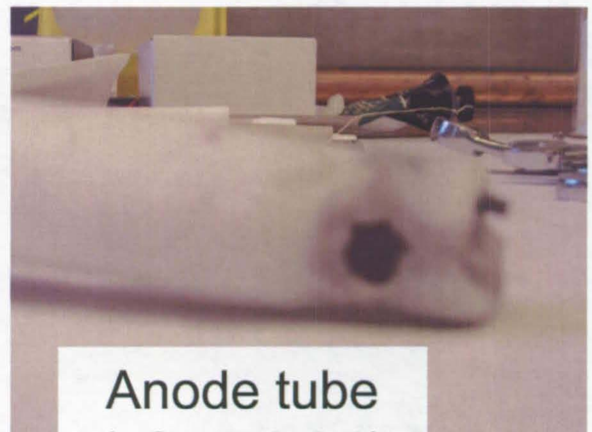
Electrolysis in Molten Oxides (trial four)







Mo cathode
(after trial 4)

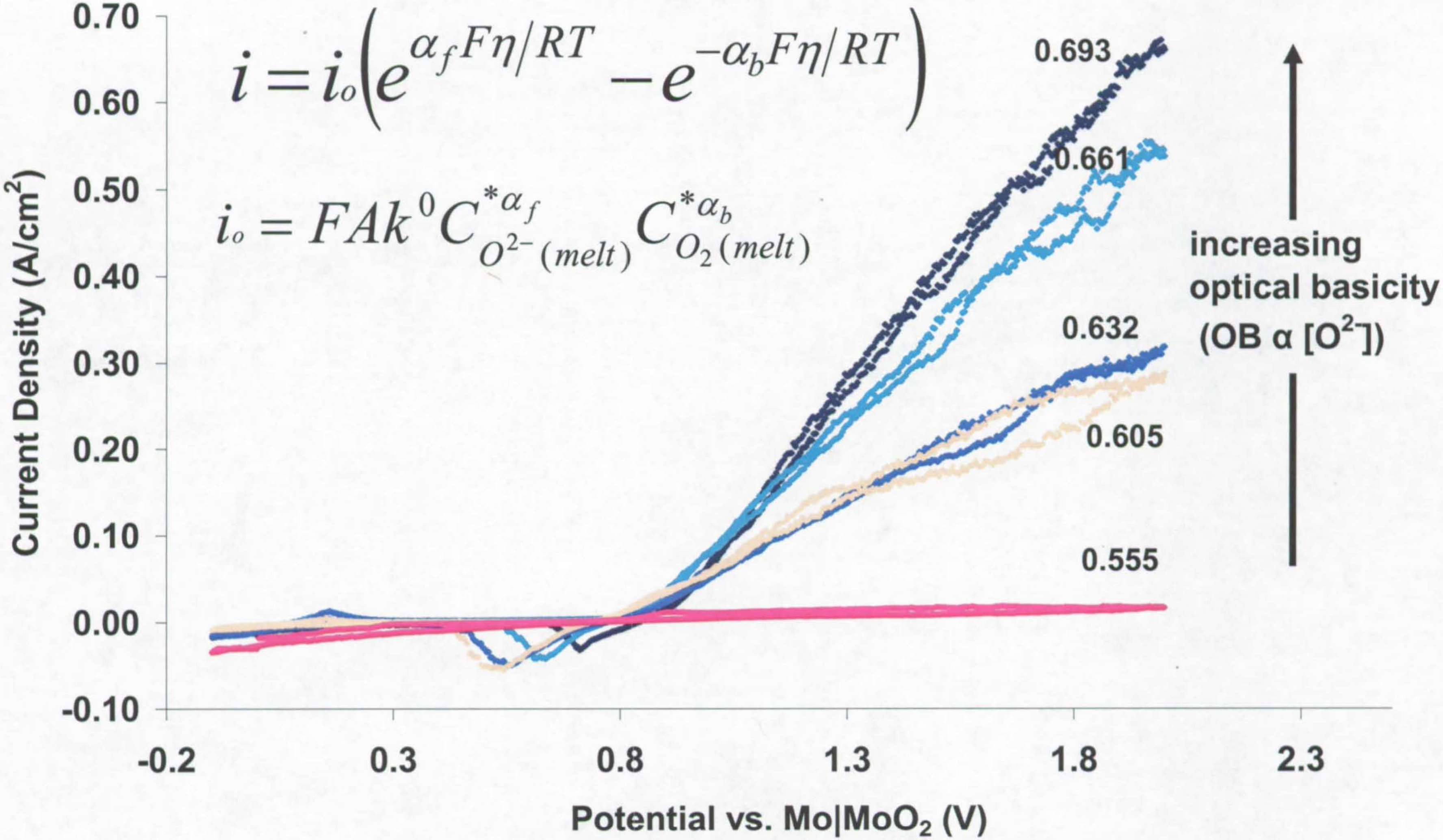


Anode tube
(after trial 4)

Iridium Current Density vs. Applied Potential in a Variety of Melts

$$i = i_o\left(e^{\alpha_f F\eta/RT} - e^{-\alpha_b F\eta/RT}\right)$$

$$i_o = FAk^0 C^{*\alpha_f}_{O^{2-}(melt)} C^{*\alpha_b}_{O_2(melt)}$$



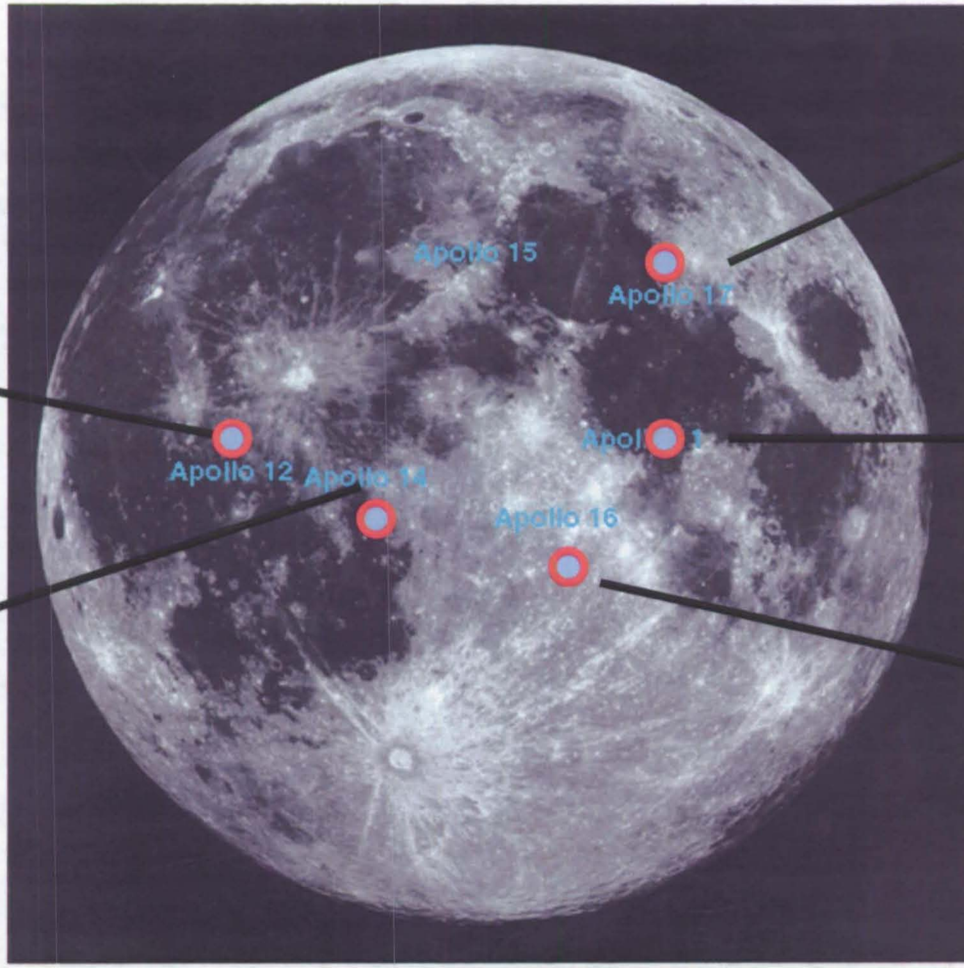
(Andrew Gmitter)

Optical Basicity of Lunar Regolith and Rocks
(higher optical basicity=higher [O^{2-}] =higher current)

Apollo 17
0.625
0.630

Apollo 12
0.620
0.607

Apollo 11
0.616
0.619



Apollo 14
0.600

Apollo 16
(deep drill)
0.589
0.586

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14. ABSTRACT
As part of an In-Situ Resource Utilization infrastructure on the lunar surface, the production of oxygen and metals by various technologies is under development within NASA projects. Such an effort reflects the ambition to change paradigms in space exploration to enable human presence for the long-term. Sustaining such presence involves the acceptance of a new concept in space activities; crews must be able to generate some of their consumables from local resources. The balance between accepting early development risks and reducing long-term mission risks is at the core of the technology development approach. We will present an overview of the technologies involved and present their possible impact on the future of human expansion in the solar system.

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ISRU, Moon, Metals processing, space exploration

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