



Production of Oxygen from Lunar Regolith using Molten Oxide Electrolysis

Laurent Sibille* and Donald R. Sadoway†

*ASRC Aerospace Corp., Kennedy Space Center, FL, 32899
Massachusetts Institute of Technology, Cambridge, MA, 02139, U.S.A.*

Aislinn Sirk‡, Prabhat Tripathy§

Massachusetts Institute of Technology, Cambridge, MA, 02139, U.S.A.

Orlando Melendez**, Evan Standish††, Jesus A. Dominguez‡‡

NASA KSC, Kennedy Space Center, FL, 32899

Ohio State University, Columbus, OH

ASRC Aerospace Corp., Kennedy Space Center, FL, 32899

Doru M. Stefanescu§§, Peter A. Curreri***, Sophie Poizeau†††

Ohio State University, Columbus, OH

NASA MSFC, Marshall Space Flight Center, AL 35899

Massachusetts Institute of Technology, Cambridge, MA, 02139

Space Propulsion and Energy Sciences International Forum
February 26, 2009, Von Braun Civic Center, Huntsville, AL



Using Space Resources is Essential to Enabling the Space Frontier



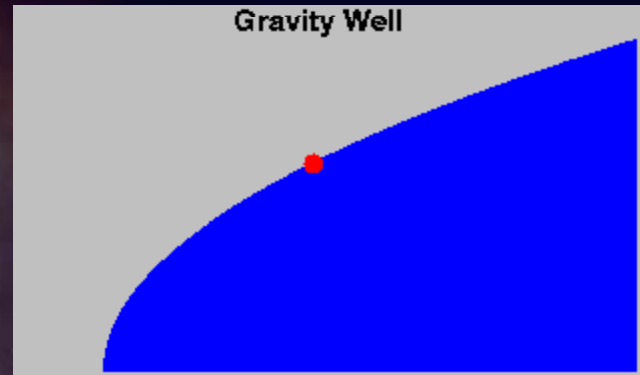
Rocket Equation

$$u = v \ln \left(\frac{M_0}{M} \right) + u_0$$

U is final, u_0 initial (rocket), v is exhaust velocity, M_0 is starting and M is ending mass (Tsiolkovsky 1903).

Saturn V

Total Mass: 2.5×10^6 kg
 Exhaust velocity: 3.0 km/s (3000 m/s)
 Burn Rate: 1.6×10^4 kg/s
 Duration: 2 min (120 sec)

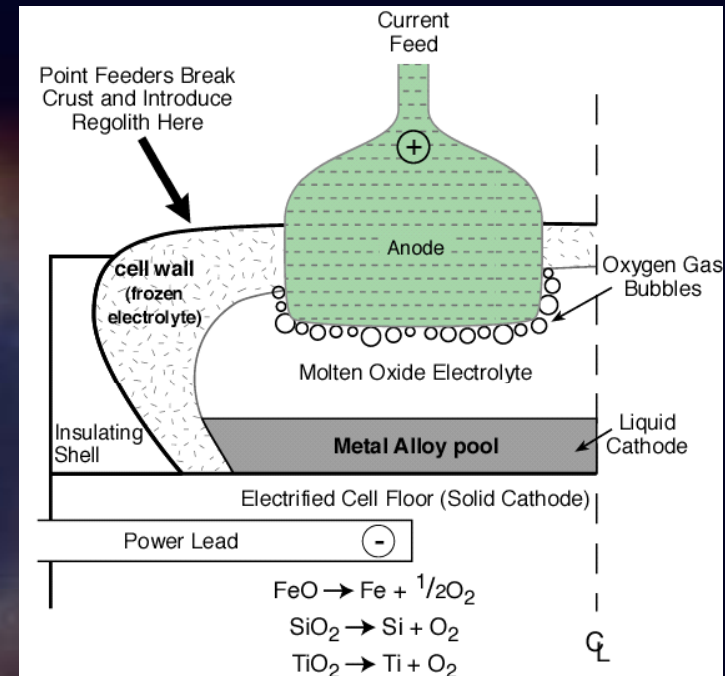
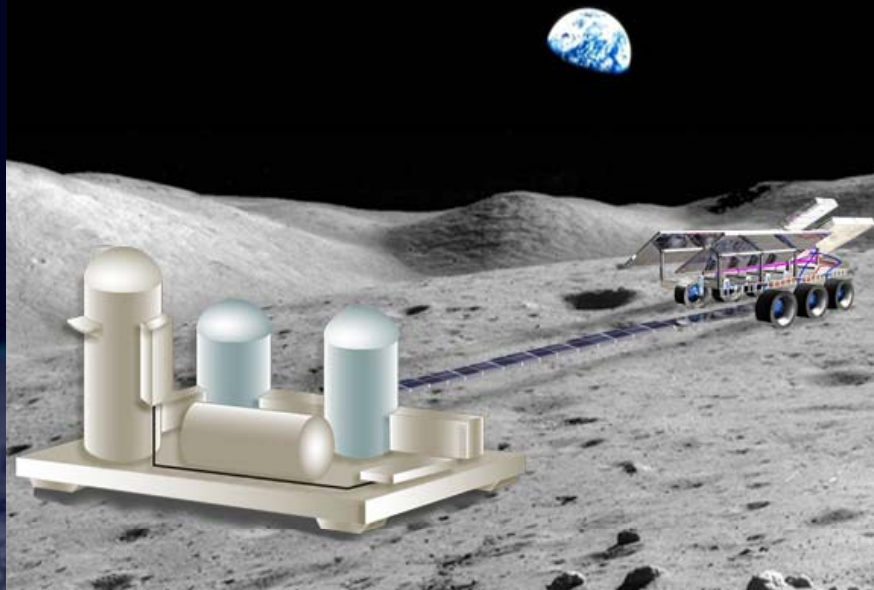


Space-time around a gravitating body is described by *Schwarzschild Geometry*, Space-time is bent by the presence of mass creating a *gravity well* which extends to the surface of the body or, in the case of a black hole, to oblivion. (John Walker)

Relative ~ Costs \$	Low Earth Orbit 10 K\$/ lb Transit Hours	Moon 100 K\$ / lb Transit Days	Mars 500 K\$ / lb Transit Months to Years	(Gold on Earth ~ \$6k/lb)
---------------------	--	--------------------------------------	---	---------------------------



Lunar Molten Oxide Electrolysis



- Molten Oxide Electrolysis, MOE:
- Requires no beneficiation and or special site
- Can produce oxygen and elements from any ore
- Could lead directly to oxygen for life support independent of Earth supply, propellant production, lunar solar power and in situ fabrication to expand base infrastructure.



Composition and Oxidative Potential of Simulant and Lunar Major Components

		JSC-1	Lunar Soil
Oxide	-E°(V)	Conc. (wt %)	Conc. (wt %)
K ₂ O	0.748	0.82	0.6
Fe ₂ O ₃	0.842	3.44	0.0
FeO	0.986	7.35	10.5
Na ₂ O	1.117	2.7	0.7
Cr ₂ O ₃	1.363	0.04	0.2
MnO	1.486	0.18	0.1
SiO ₂	1.757	47.7	47.3
TiO ₂	1.822	1.59	1.6
Al ₂ O ₃	2.179	15.02	17.8
MgO	2.376	0.18	0.1
CaO	2.590	0.04	0.2

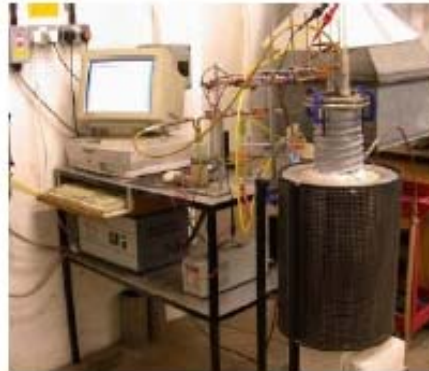
Oxidative Decomposition Potentials at 1300°K
vs. wt% JSC-1 and Lunar Soil Major Elements



Regolith Salt & Molten Electrolysis For O₂ Extraction



Early Electrolysis Cell Test
at MSFC



Ilmenox (FFC Process)
Cell at FIT



Molten Electrolysis
Cell at MIT



Furnace cap with O₂
collection device



Anode Electrode Lost in Melt



Electrowinning Experiment Melt



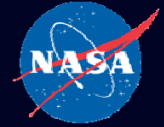
View of the new 10in furnace

- Highest oxygen yield (up to 40% oxygen yield by mass) plus metals: Fe, Al, Si
- Highest technical risk –molten material containment, molten handling, high oxidation resistance, long-life electrodes
- One step to create oxygen



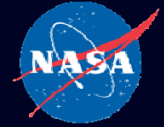
Direct Electrowinning of Oxygen and Metals

- Earth industry produces aluminum and magnesium dissolving pure oxides into halide salts for electrolysis
- The advantage of halide salt electrolytes is that they lower the process temperature
- The disadvantage is that the salts are tailor made for each oxide and have a low saturation limit (4-5%)
- Space applications favor multi-oxide mixture to eliminate beneficiation
- The direct electrolysis of lunar regolith in its own melt eliminates the dissolution limit of salts and allows a high reactor mass to feed mass ratio (small footprint)



Project and Program Goals and Accomplishments

- Production of oxygen by electrolysis of molten regolith simulants at near 1600 C.
- Inert anode (oxygen production) suitable cathode (metal Production)
- High oxygen production rates in a small foot print lunar facility with minimum consumables from Earth
- Benchmark goal 1 metric ton Oxygen per year
- Present laboratory cell charge of 500 g and current of several Amperes
- Model to balance external heating and internal joule heating



Electrochemical Measurements and Reactor Performance

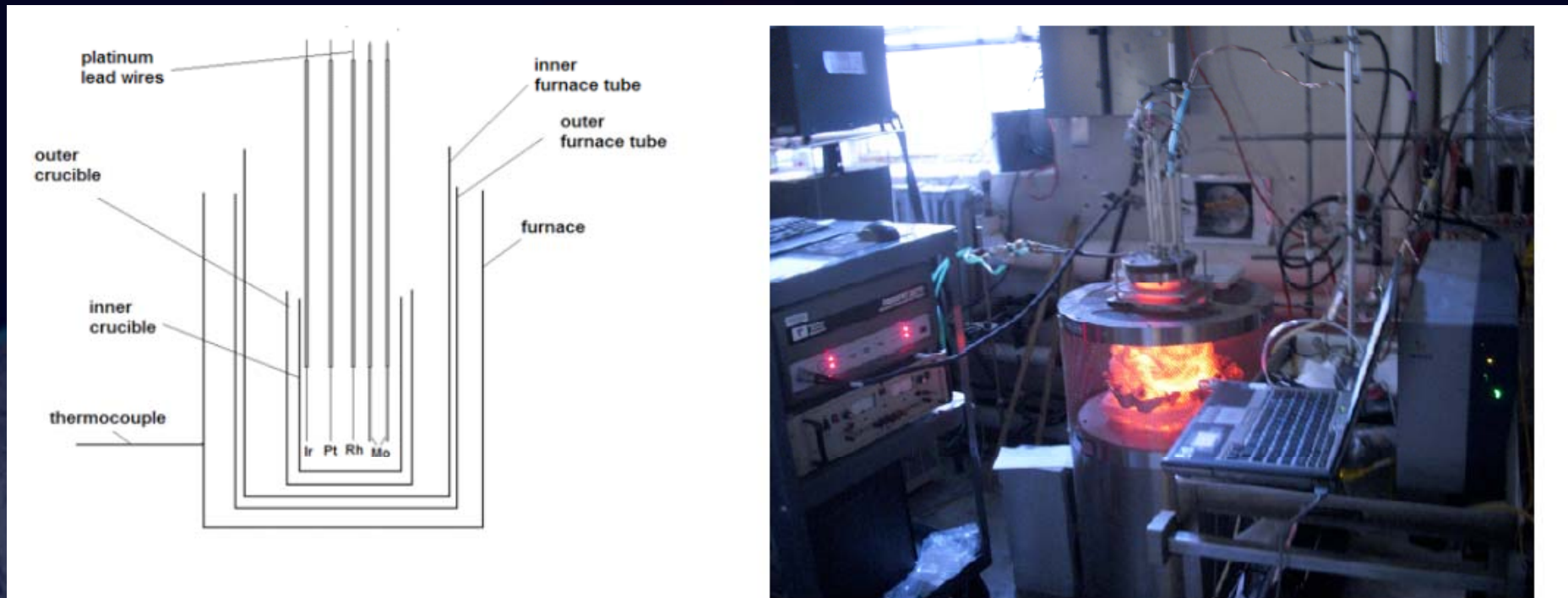
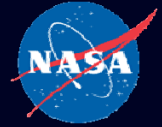


Figure 1. Schematic of electrolytic cell configuration to investigate electrochemical behaviors of various anode materials in molten oxides (left) and furnace containing the cell in operation at 1600 °C (right). The micro gas chromatograph is seen on the right of the image.

Laboratory of Prof. D. Sadoway at MIT



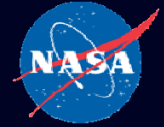
Electrochemical Measurements and Reactor Performance

The current efficiency at either electrode is defined as the portion of the current passed that is used to generate the product. The rate of production is proportional to the current efficiency according to Eq. (1).

$$rate = \frac{jA}{nF} \times Efficiency \quad (1)$$

where j is the current density, A is the surface area of the electrode, n is the number of electrons involved, and F is the Faraday constant.

Anode current was measured using an electrochemical workstation and oxygen production was measured using a Varian micro-gas chromatograph. These measurements along with cell geometry allow the determination of reactor efficiency.



Electrochemical Measurements and Reactor Performance

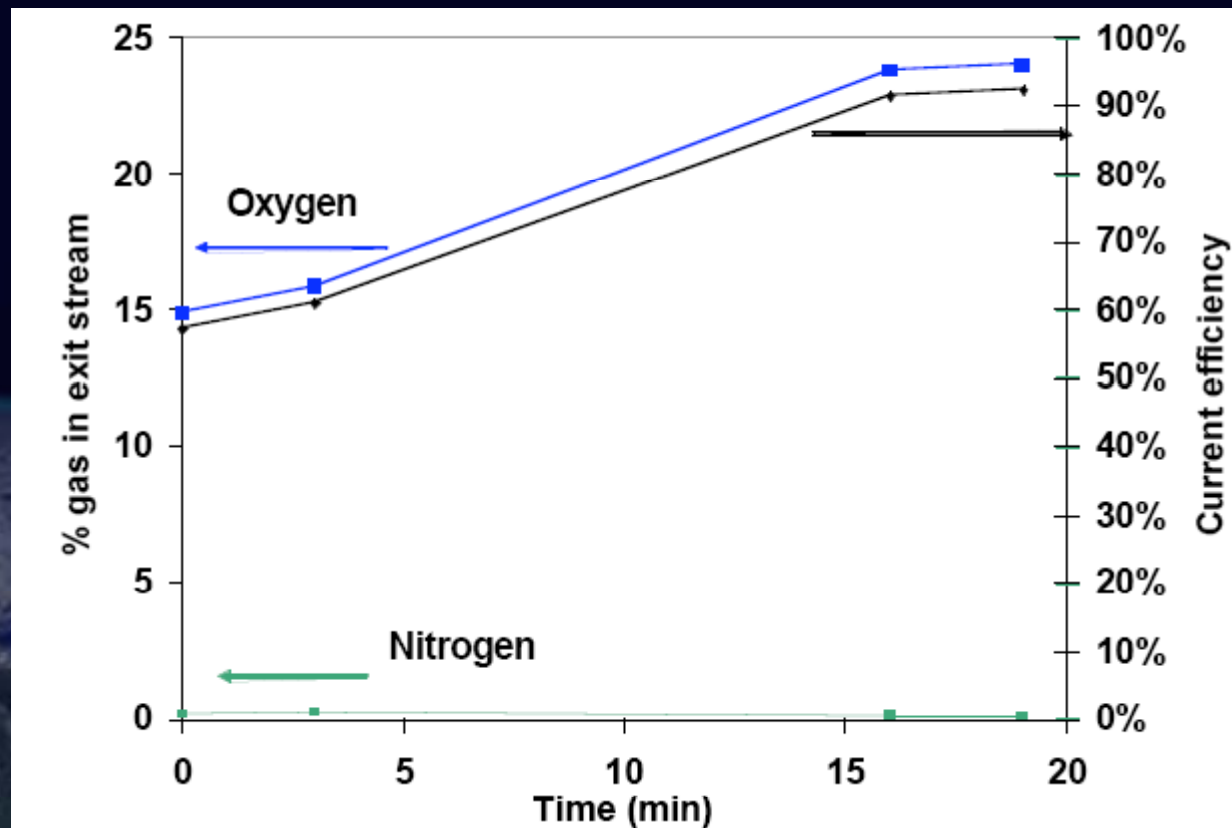


Figure 2. Anodic current efficiency from direct measurements of oxygen generated during electrolysis at 1600 °C from an oxide melt of chemical composition of JSC1A simulant without iron oxides.

Electrochemical Measurements and Reactor Performance

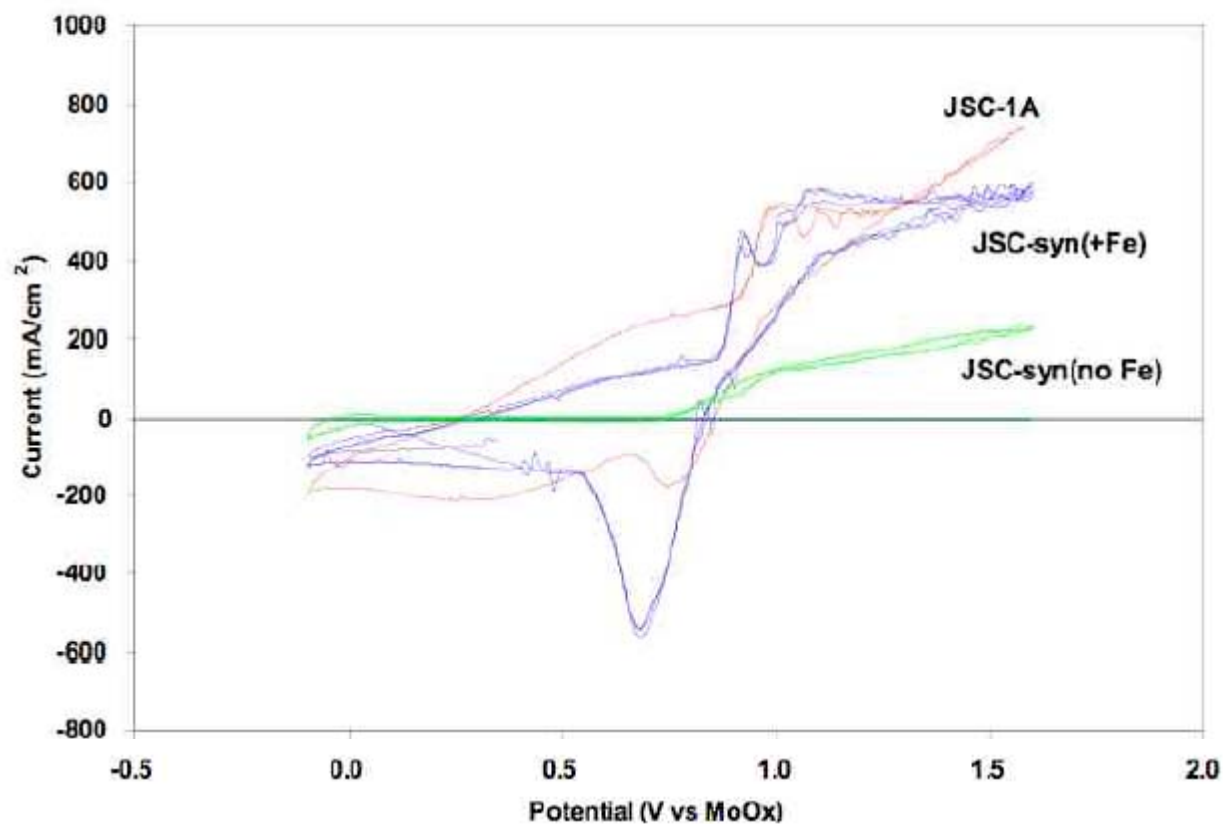
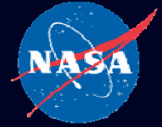


Figure 3. Effect of iron in oxide electrolytes on the current density.



Electrochemical Measurements and Reactor Performance

Optical Basicity

$$\Lambda_{melt} = \frac{\sum_i x_i n_i \Lambda_i}{\sum_i x_i n_i} \quad (1)$$

where x_i is the mole fraction of oxide i ; n_i is the number of oxygen per mole of oxide i ; and Λ_i is the basicity of oxide i .

Optical Basicity correlates composition of molten lunar soil with expected current density that the melt can support during electrolysis i.e. the expected reactor oxygen production efficiency.

Gmitter and Sadoway, MIT

Electrochemical Measurements and Reactor Performance

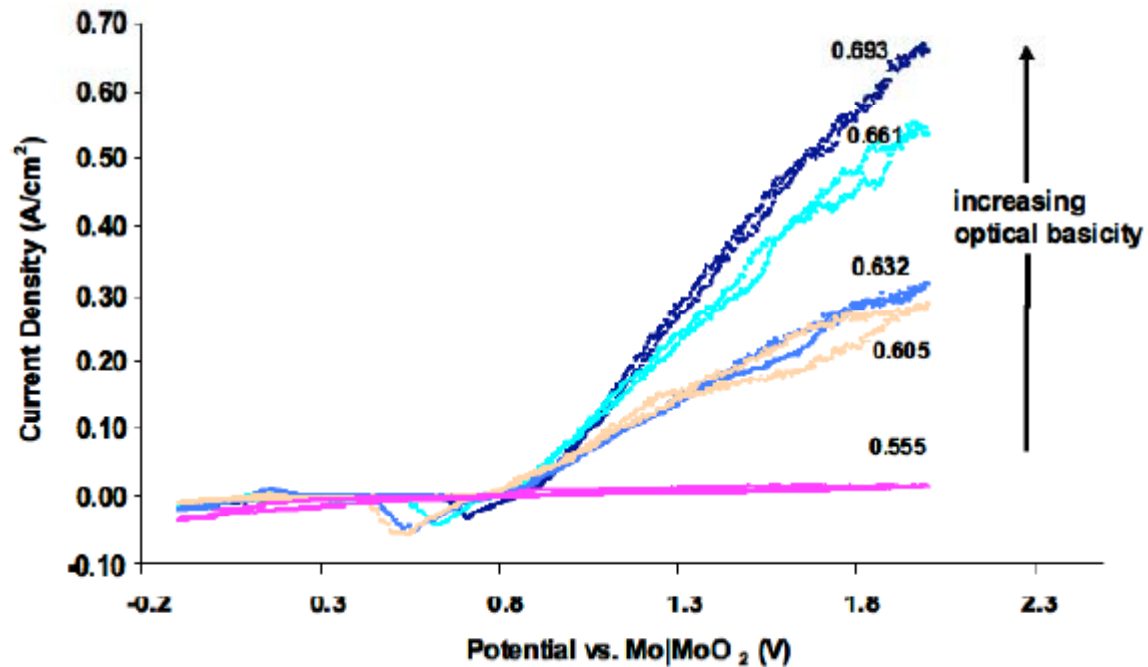
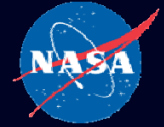


Figure 4. Current densities sustained in oxide melts of different optical basicities (Ir anode)



Electrochemical Measurements and Reactor Performance

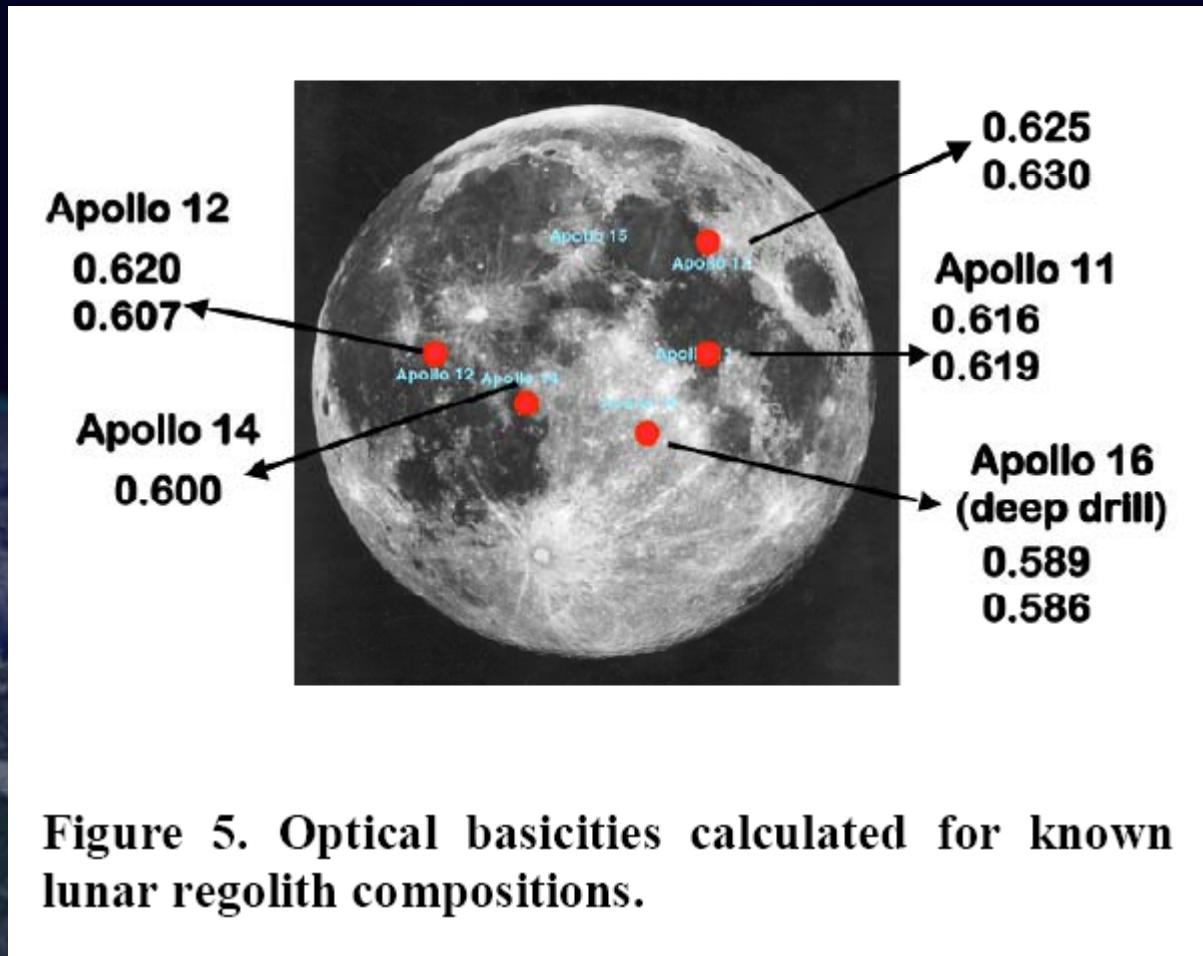


Figure 5. Optical basicities calculated for known lunar regolith compositions.

Values of optical density are similar for known lunar landing sites suggesting that Molten Regolith Electrolysis efficiency is site independent

Development of inert electrodes

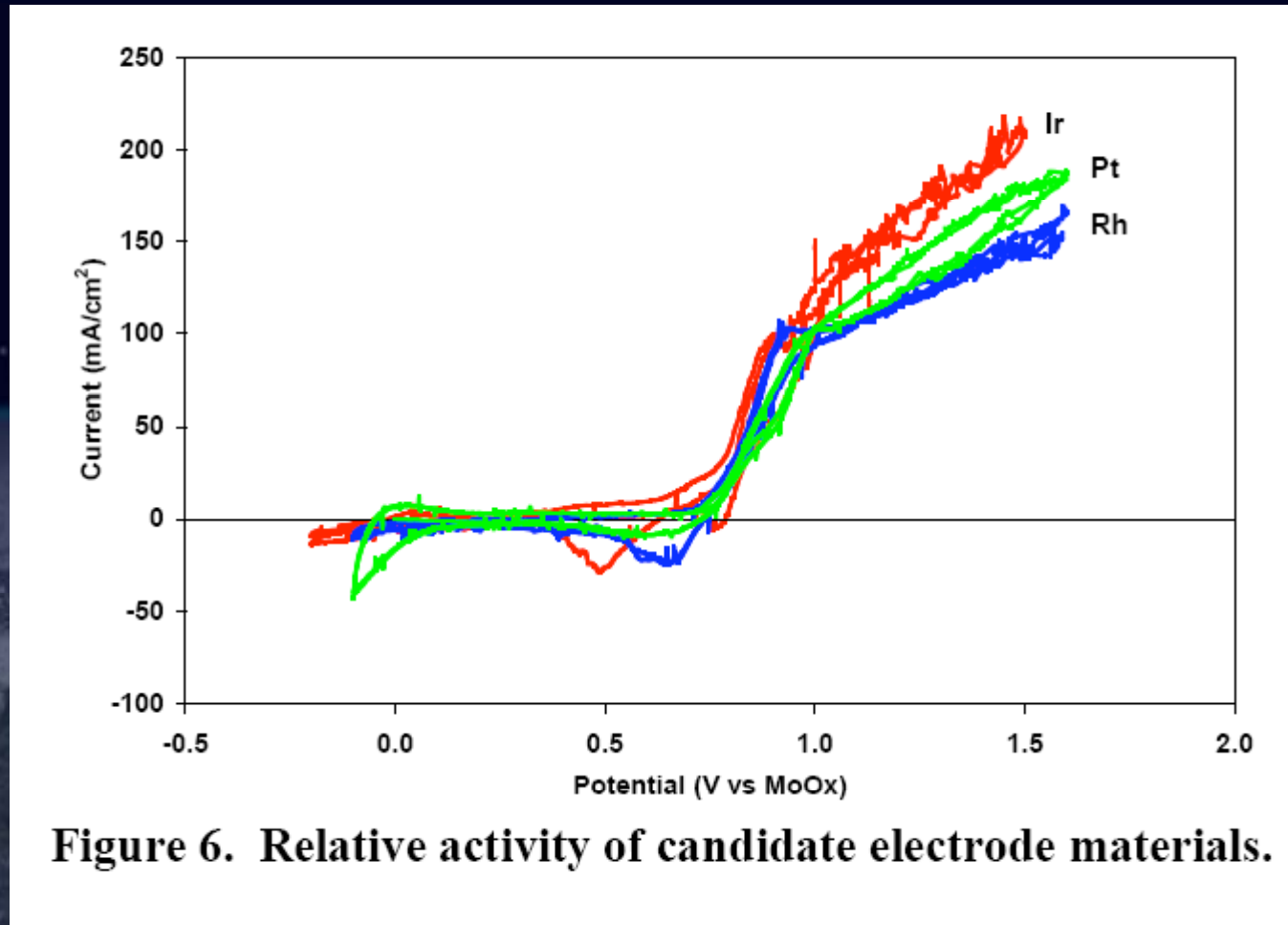


Figure 6. Relative activity of candidate electrode materials.

Electrodes must withstand molten oxide at 1600 C, resist oxidation, and maintain high conductivity while avoiding frequent replacements.

Development of inert electrodes

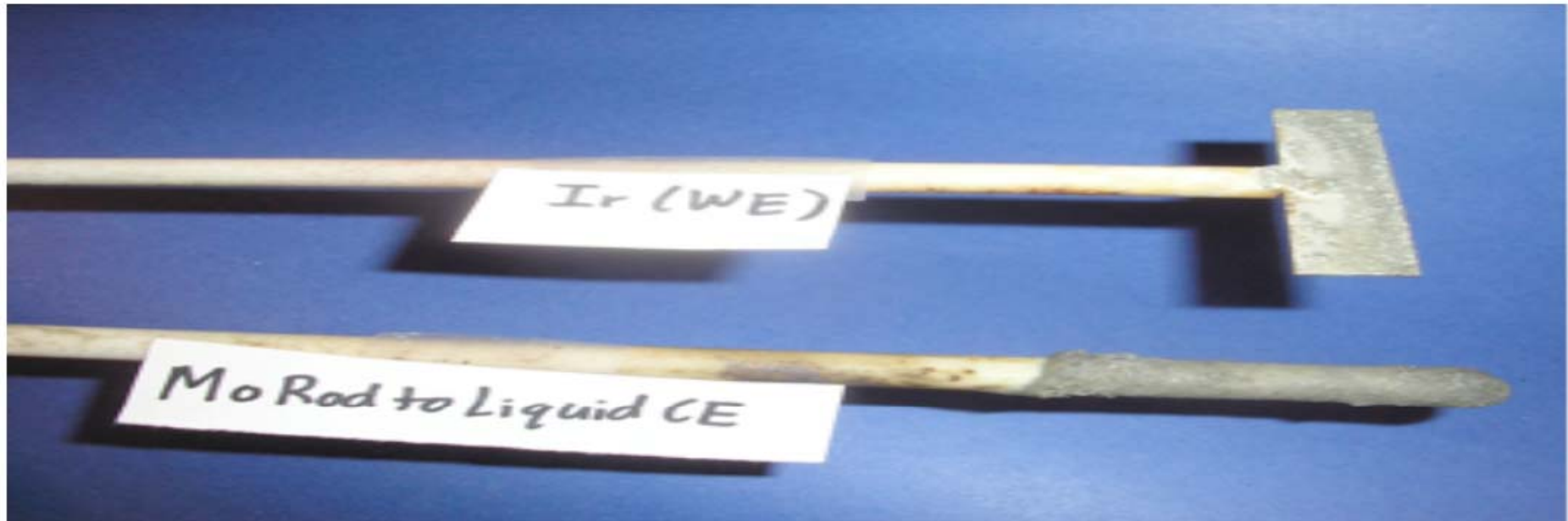


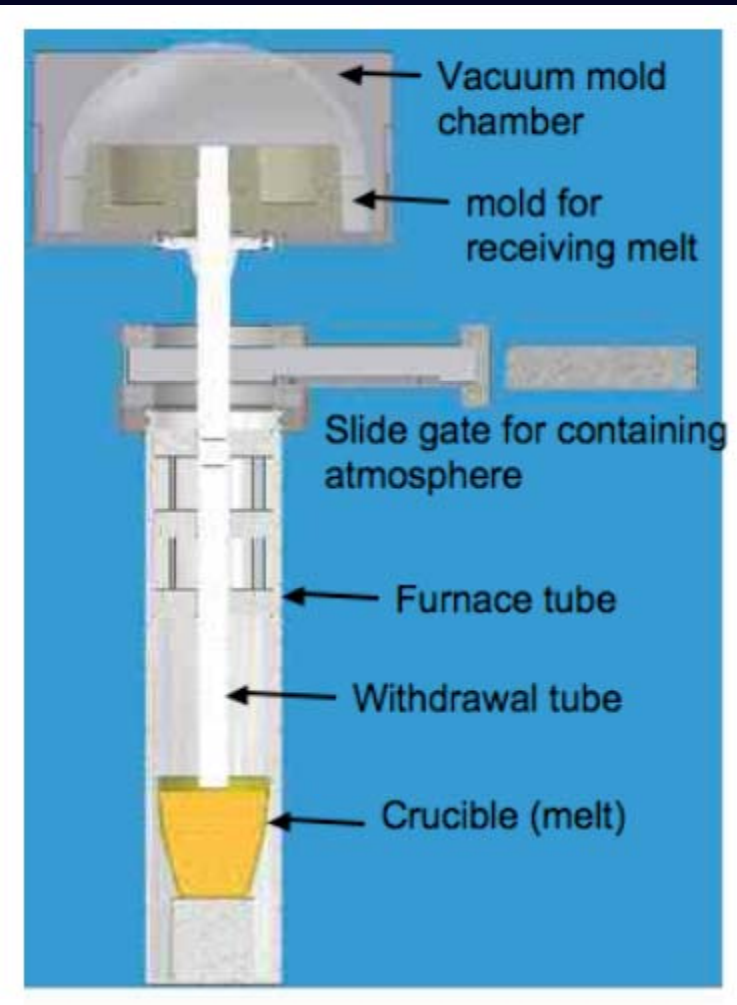
Figure 7. Anode of Iridium (10 cm^2) and cathode collector of Molybdenum after electrolysis test passing currents of 3 A.

Iridium based anodes and molybdenum based cathodes have survived repeated 8 hour laboratory Molten Regolith Electrolysis cycles.

Withdrawal of Molten Materials

To move from batch to continuous operations, a system is being tested to feed lunar regolith and withdraw spent electrolyte and metallic products.

Figure 8. Schematic of counter gravity Molten Material Withdrawal device (Ohio State U.).



Heat Transfer Modeling (Joule heating)

The aluminum industry uses a crust of aluminum oxide and electrolyte as the reactor wall. This is called a “cold walled” reactor. The “hot walled” furnace and crucible systems being used for laboratory experiments have severe containment problems, thus we envision the lunar reactor to also be “cold walled.”

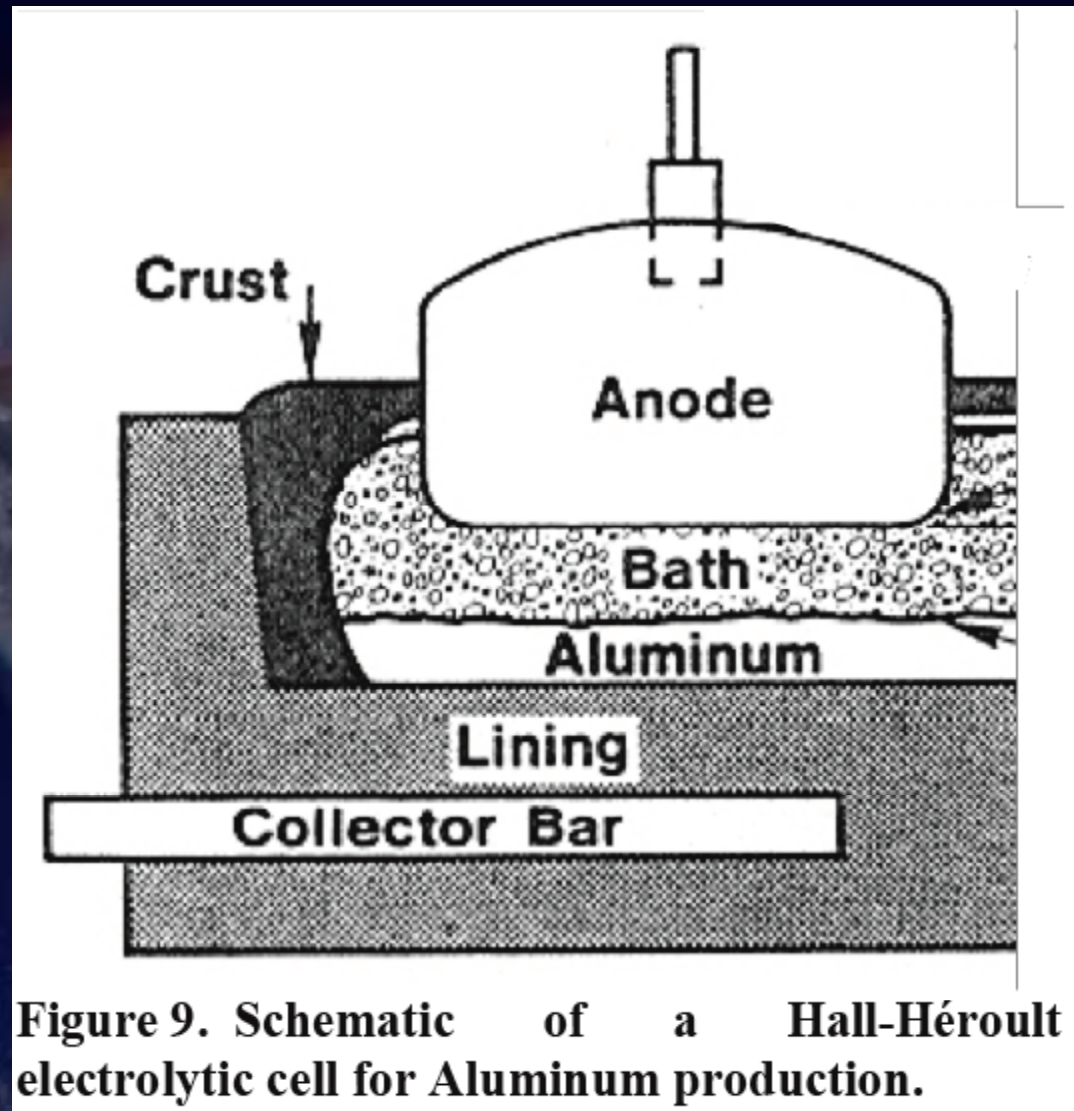


Figure 9. Schematic of a Hall-Héroult electrolytic cell for Aluminum production.

Heat Transfer Modeling (Joule heating)

Aluminum industry electrolysis reactors are size to be large enough to so that the heat from the electrolysis is sufficient to maintain the required cell temperature. Thus, these reactors are called “self-heating.”

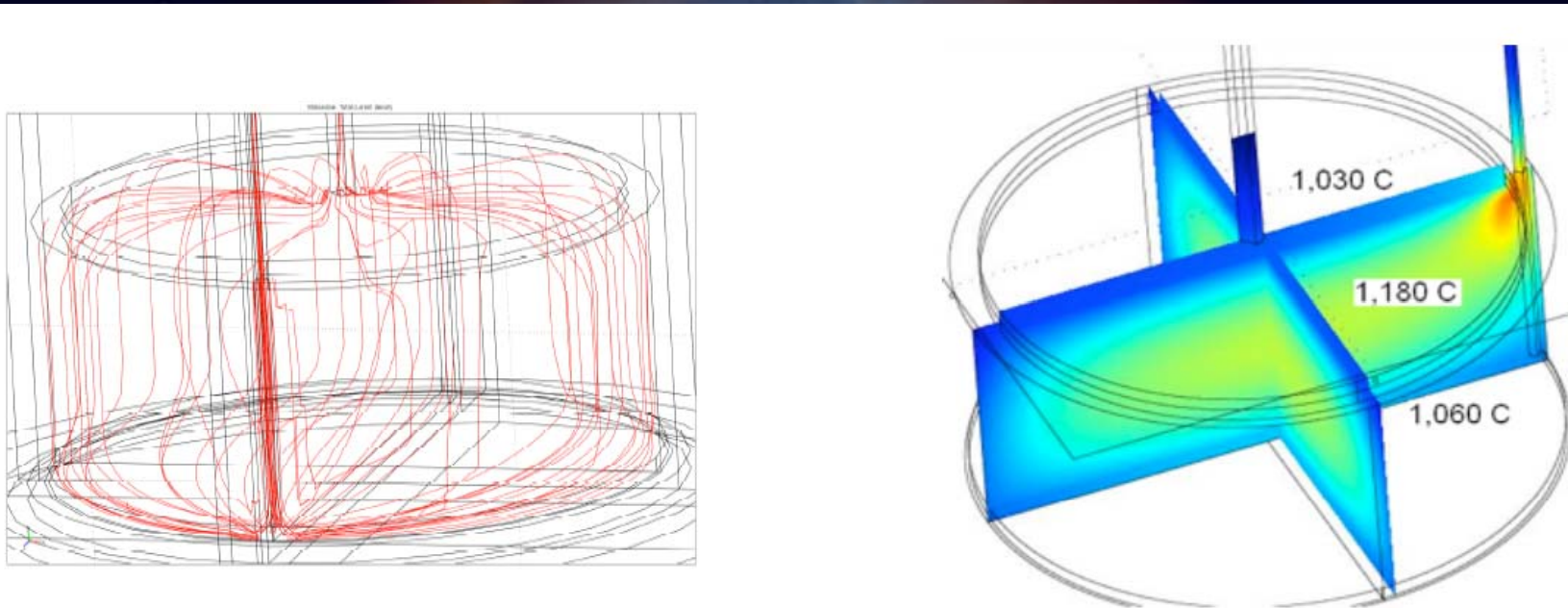


Figure 10. Lines of current through a molten regolith electrolysis cell (left) and corresponding melt temperatures generated by Joule heating (right). The anode is outline as a disc-shape plate at the top of the volume electrically connected by its central lead; the cathode collector runs vertically along the side to the disc-shape cathode at the bottom of the volume.



Conclusions

- Molten Regolith Electrolysis has advanced to be a viable method for production of oxygen and metals in situ on the Moon.
- We have demonstrated 8 hour batch electrolysis at 5 amps using Iridium inert anodes.
- Iron in different oxidation states was found to have a parasitic effect due to electronic conduction, reducing anodic current efficiency for oxygen production.
- Current efficiency of near 100% is observed once the iron is depleted suggesting batch processing efficiency is near 94% after 34% of the regolith total oxygen has been captured.
- Feed and withdrawal devices are being developed to allow continuous operations.
- Thermal modeling of the reactor is being done to determine the reactor size necessary for self heating.



Acknowledgments

The authors wish to thank NASA Exploration Technology Development Program and the ISRU Project for funding this effort and NASA Kennedy Space Center and Marshall Space Flight Center for their support.