Update Commercial Lunar O$_2$ Analysis

Bruce Pittman/ARC
Robert M. Kelso/JSC
Jerry Sanders/JSC

September 2010 LEAG Meeting
Background

✔ Risk Adjusted Net Present Value
  - commonly used by industry and VC to assess different business options

✔ NASA – “cost to government” more appropriate
  - RANPC (ex: COTS analysis)

✔ Current Lunar Commercialization assessments for early access to lunar surface
  - Supporting exploration flight test opportunities
    • Risk reduction/cost avoidance
    • ISRU flight demonstrator for O2 extraction from regolith
    • LSS: “…could be game-changing”

✔ DIO authorized funding of study in Feb 2009
ISRU Oxygen Production Cost Study

❖ ISRU a critical capability of exploration planning.
❖ Demand portfolio for oxygen production:
  – Crew habitat and EVA O₂ requirements
  – Ascent Propulsion O₂ requirements
  – Crew habitat, EVA, and Small Pressurized Rover water (H₂O) requirements
❖ RANPC study to assess price points for producing lunar O₂ as alternative to transporting it from earth
❖ GOAL: define financial case for determine degree of cost saving for the two O₂ supply options
Analysis Plan

- Determine Lunar surface $O_2$ demand to support NASA surface operations
  - Develop quantities of $O_2$ required
  - Define assumptions to be used
- Define options to be analyzed
- Review results of previous studies
- Establish a risk and cost structure for each option
- Collect required data and perform analysis for each option
- Perform RANPC analysis
Lunar O₂ Demand

❖ Crew habitat and EVA O₂ requirements
  – 1000 kg/yr supports closing life support system for crew of 4

❖ Ascent Propulsion O₂ requirements
  – 6000 -7000 kg/yr supports two Altair ascent stages to LLO per yr
  – ? Kg/yr to support reuse of Altair descent stage for return to LLO

❖ Crew habitat, EVA, and Small Pressurized Rover water (H₂O) requirements
  – 350 – 400 kg/yr ave. H₂O needed to life support system for crew before permanent stay
  – 4700 kg/yr H₂O needed after permanent stay starts

❖ Note: ~450 kg H₂O extra per mission possible by scavenging remaining hydrogen (H₂) from Altair descent tanks and adding 400 kg of O₂ from ISRU; 1350 kg H₂O with 1200 kg ISRU O₂ for 3 missions per year
The Commercial MINER Program
Commercial Lunar Oxygen

NASA & Commercial Tractor Recover Oxygen from the Lunar Regolith
MINER Concept Overview

✓ **GOAL** – provide operational data for lunar O$_2$ production with regolith using industry partnership
✓ Lunar ISRU O$_2$ flight experiment: design and performance scalable to Outpost production method
✓ Low weight/low power/low cost
  – <50kg experiment flight package
  – Low cost, commercially leveraged
✓ Operate for as long as possible with multiple cycles
✓ Option for science instruments for chemical content
  – Leveraging SMD dollars
✓ Public engagement
MINER Resource Characterization & Oxygen Production Demonstration Hardware

Lander-Based Experiment

Lunar Science & ISRU Characterization Functions
- Optical inspection (Camera & microscope)
- Combined XRD-
- Mass spectrometer (MS) and/or gas chromatograph (GC)

Critical ISRU O₂ Production Functions

Phoenix Arm/Scoop
- Excavate lunar regolith and deliver to experiment
  - Mass (kg): 8.12
  - Power Ave. (W): 56
  - Dimensions (cm): 146.5 x 26.8 x 21.7
  - Heritage: Flight hardware
  - Note: More force/torque may be required

CHAMP
- Visual & microscopic evaluation
  - Mass (kg): 1.4
  - Power Ave. (W): 1
  - Dimensions (cm): -
  - Heritage: Field hardware
  - Note: More work required to estimate

Beneficiation Unit
- Concentrate iron-bearing minerals
  - Mass (kg): 11.34
  - Power Ave. (W): 200
  - Dimensions (cm): 49 x 25 x 13
  - Heritage: Lab. hardware
  - Note: Did not use flight weight valving or chamber

RESOLVE Reactor
- Perform volatile extraction and H₂ Reduction
  - Mass (kg): 17.90
  - Power Ave. (W): -
  - Dimensions (cm): 10 x 16 x 9.5
  - Heritage: Modified COTS hardware
  - Note: Based on Mars MIMOS II instrument

RESOLVE Fluid System
- Collect, capture, and measure gases
  - Mass (kg): 4.40
  - Power Ave. (W): -
  - Dimensions (cm): -
  - Heritage: Lab. hardware
  - Note: Did not use flight weight valving and fittings

RESOLVE GC
- Characterize volatiles and H₂O production
  - Mass (kg): 0.50
  - Power Ave. (W): 2
  - Dimensions (cm): -
  - Heritage: Modified Flight Design
  - Note: Under development for SMD

Combined Mossbauer
- Measure minerals and iron/iron-oxide content
  - Mass (kg): 6.1
  - Power Ave. (W): 1
  - Dimensions (cm): -
  - Heritage: -
  - Note: -

Optional Instruments
- Micro-LIBS Raman
  - Characterize minerals
    - Mass (kg): 3.1
    - Power Ave. (W): 20
    - Dimensions (cm): -
    - Heritage: Lab. hardware
    - Note: Under development for SMD

- Viking GCMS
  - Characterize volatiles and H₂ reduction
    - Mass (kg): 10.40
    - Power Ave. (W): -
    - Dimensions (cm): -
    - Heritage: Lab. hardware
    - Note: Flown on Beagle II

- VAPoR MS
  - Characterize volatiles and H₂ reduction
    - Mass (kg): -
    - Power Ave. (W): -
    - Dimensions (cm): -
    - Heritage: Lab. hardware
    - Note: Under development for SMD

- APXS
  - Characterize minerals
    - Mass (kg): -
    - Power Ave. (W): -
    - Dimensions (cm): -
    - Heritage: Flight hardware
    - Note: Flown on Mars landers
Oxygen Production System - ISRU

Functional Description:
Perform lunar regolith excavation and handling, oxygen (O₂) extraction from regolith, and oxygen storage and delivery. Supports lander propellant scavenging and water production. For flexibility, two 1/2-scale Oxygen Production Systems (OPSs) will be delivered and 2 sets of excavation tools.

- Total O₂ produced per plant = 500 kg/yr (solar) & 600 kg/yr (nuclear)
- Mass per O₂ plant = 219 kg
- Power per plant = 3.93 kW
- Total regolith per plant = 208 kg/day
- Excavation Tools = 42.7 kg (each)
- Excavation Time = <1 hr/day
Assessment Options

✓ Option 1
  – All $O_2$ and $H_2O$ requirements are supplied from Earth using the Constellation architecture

✓ Option 2
  – All $O_2$ and $H_2O$ is supplied from Lunar regolith using ISRU

✓ For each option two different $O_2$ requirements will be assessed
  – Option A 2000kg/yr - $O_2 +$ Water
  – Option B 9000kg/yr - $O_2 +$ Water+ascent propulsion
    • Does not include 4500kg of water required after permanent stay starts
ISRU Demonstration Missions

- Two Lunar $O_2$ demo extraction missions are included in cost estimates
  - 50 kg each delivered to Lunar surface in ~2014
- The purpose of the demo missions is proof of concept and operation of the $O_2$ extraction and is a key element in buying down the ISRU risk
- Two different extraction processes will be evaluated
- Two different companies will be utilized to ensure competition
Assumptions

- This analysis covers the period 2020-2030 based on first crewed landing in 2020
- No other ISRU products are considered
- Option 1 assumes only transportation cost no dev or ops cost
- No Lunar water assumed in this analysis
- Two 50kg O₂ extraction and storage demo missions are included in the ISRU development costs
  - ISRU demos used to buy down risk
  - Demo flights costed at $1M/kg development and $1M/kg lunar transport
- ISRU production unit assumes Constellation price for Lunar surface delivery of $150k/kg and development cost of $250k/kg
- ISRU production plant will be operational prior to 2020
- ISRU operations replacement mass is 15%/year
- ISRU development and operation is government funded/contractor developed/operated using standard FAR procurements
## RANPC Analysis Results

<table>
<thead>
<tr>
<th>Option</th>
<th>Development ($B)</th>
<th>Transportation ($B)</th>
<th>Operations 11 yrs ($B)</th>
<th>Total ($B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1A</td>
<td>0</td>
<td>3.3</td>
<td>0</td>
<td>3.3</td>
</tr>
<tr>
<td>2T/yr Ares 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option 1B</td>
<td>0</td>
<td>14.9</td>
<td>0</td>
<td>14.9</td>
</tr>
<tr>
<td>9T/yr Ares 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option 2A</td>
<td>.45</td>
<td>.15 (1000kg)</td>
<td>.644</td>
<td>1.24</td>
</tr>
<tr>
<td>2T/yr ISRU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option 2B</td>
<td>.8</td>
<td>.36 (2400kg)</td>
<td>1.69</td>
<td>2.85</td>
</tr>
<tr>
<td>9T/yr ISRU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lunar RANPC Results & Conclusion

✔ ISRU has potential to save >$1B/yr (Option 2B scenario)
  - >5X ROI

✔ ISRU costs estimates are heavily influenced by ops costs

✔ There is the potential for commercial leverage that was not addressed in this analysis

✔ The Constellation transportation costs are optimistic and ISRU cost saving improve as transportation costs increase

✔ This analysis used a conservative set of assumptions

✔ Using ISRU does not require significant change to Constellation architecture

✔ Conclusion - This analysis was undertaken to determine if ISRU has the potential for significant Constellation cost savings and the definitive answer is - YES!
Recommendations

✔ Up front ISRU technology development is a good investment
  - Robotic/teleoperations technology for production, storage, and transfer of lunar $O_2$
  - Terrestrial analogs are good first step

✔ Further cost savings could be achieved in demo and production using commercial leveraged fixed price commodity purchase contract
  - More detailed analysis of ISRU commercial leverage risks and opportunities is needed
  - Need to keep it competitive - 2 suppliers and two processes

✔ More detailed analysis of ISRU operations cost reduction potential is needed

✔ Other ISRU product benefits beyond oxygen should be explored
  - Si, Fe, Ti, Mg, Al, H
Technical Risk

- Extraction technology does not perform as predicted
- Equipment breaks down; repair delays reduce production
- Yield is low/degrades - insufficient O₂ available
- Storage tanks under perform/fail
- Equipment for Lunar O₂ transfer fails to perform
- Launch/landing vehicle fails in to deliver payload to Lunar surface

- These risks can be reduced to acceptable levels with successful demo mission(s)
ISRU RANPC Questions/Issues

❖ Ability to have O₂ extraction demonstrated and O₂ available prior to 1st crewed mission?
❖ Non-monetary value to ISRU
  – Robustness/flexibility for Lunar outpost
  – Scientific benefit from near term demonstration
  – Extraction of other materials other than O₂
❖ What are the programatic risks and how can they be addressed?
❖ Potential for commercial leverage for demonstration mission(s)?
  – What is the best business arrangement?
  – Is there a customer other than NASA?
  – Potential for using a prize for Lunar O₂ demo?
What’s New?

- Augustine Committee and 2011 NASA budget
- LRO and LCROSS
- Water on the Moon, a lot of water
  - South Pole, North Pole, ???
  - Stories of as much as 600 million tons on the North Pole
- Extraction of the water
  - Something as simple as a microwave could be all that is needed
  - This would greatly simplify extraction process
- Do we still need O2/H2O if Constellation is cancelled?
  - Fuel depots may be one answer
  - Commercial lunar activity such as Bigelow could be another
- Goggle Lunar X Prize
  - 22 teams and growing
- NASA ILDD BAA
  - $30.1 million available
Lunar Research Park & University

Lynn Harper
Dan Rasky
Bruce Pittman

NASA Emerging Commercial Space Office
What Comes After “Flags & Footprints”?

✔️ If the ultimate goal of exploration is settlement, how do you get there from here?

✔️ What is needed is a “compelling” vision of the future that can activate, align and sustain the various constituent elements
  - Political/legal
  - Social
  - Scientific
  - Engineering
  - Economic
  - Educational
Key Elements

- Permanence
- Expandability
- Functional diversity
- Organizational diversity
- Frequent transportation between Earth and the Moon
- Flexibility
- Phasing
- Broad participation
  - US government
  - Commercial
  - University
  - International
  - Media
  - Public
Development Phasing

✓ Terrestrial analogs
✓ Robotic precursors
✓ Teleoperations
✓ Infrastructure development
  – Resource depot
  – Space tug
  – Reusable lunar orbital transfer vehicle
  – Lunar comm/nav
  – Lunar power beaming
  – Reusable lunar landing
  – Lunar habitation (Bigelow?)
Japanese/US Technology and Space Applications Program (JUSTSAP)

The Next Giant Leap: Building Sustainable Settlements Beyond Low-Earth Orbit

November 14-18, 2010

Jim Crisafulli, Director, Office of Aerospace Development

Frank Schowengerdt, Director PICES, University of Hawaii, Hilo

Fairmont Orchid, Kohala Coast, Island of Hawaii

Key topics:

- Building Sustainable Settlements Beyond LEO
- Establishing a Multinational Lunar Research Park
- Bringing Space Settlement Down to Earth
- Use of Authorities for Development of Settlements Beyond LEO
- Lunar R&D Park Conceptualization
Backup Charts
ISRU Operations Cost Breakdown

✔ Option 2A - 2000kg/yr of Lunar O₂
  - $36 million/yr operations cost
  - $22.5 million/yr for shipment of 150kg (15%) of replacement parts

✔ Option 2B - 9000kg/yr of Lunar O₂
  - $86 million/yr operations cost
  - $67.5 million/yr for shipment of 450kg (15%) of replacement parts

✔ The operations costs are ~ 50% personnel/50% parts
✔ The parts cost are ~ 50% of the development cost
References

✓ Personal Correspondence:
  – Vicki Gutierrez - NASA JSC - Constellation Lunar delivery cost
  – Edward McCullough - Consultant - Lunar O₂ extraction
  – Dennis Wingo - SkyCorp - Lunar operations

✓ Books, Papers and Presentations:
  – D. Wingo, MOONRUSH: Improving Life on Earth with the Moon’s Resources, 2004