Introduction to Space Resource Mining

International Space University
Space Studies Program - SSP13

STRASBOURG, FRANCE
JULY 15, 2013

Robert P. Mueller
SENIOR TECHNOLOGIST
SURFACE SYSTEMS OFFICE - NASA
KENNEDY SPACE CENTER, FLORIDA, USA
Introduction

- NASA Senior Technologist specializing in Space Mining, Robotics, Regolith, In-Situ Resource Utilization and Space Systems Engineering
- B.Sc. Mechanical Engineering – University of Miami, Florida, USA
- M.S. Space Systems Engineering – TU Delft, Netherlands, EU
- M.B.A. Business Administration - Florida Institute of Technology, USA
- Worked at Kennedy Space Center (KSC), Johnson Space Center (JSC) & Jet Propulsion Lab (JPL) since 1989
The Swamp Works is a new KSC facility designed for Innovation and Lean Development of New Space Technologies.

KSC Swamp Works establishes rapid, innovative and cost effective exploration mission solutions through leveraging of partnerships across NASA, industry and academia.

New way of doing business – back to the future:

Wernher Von Braun and Kelly Johnson both used these methods.
The NASA Mission
Drive advances in science, technology, and exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth.

Overarching Strategies
- Investing in next-generation technologies and approaches to spur innovation
- Inspiring students to be our future scientists, engineers, explorers, and educators
- Expanding partnerships with international, intergovernmental, academic, industrial, and entrepreneurial communities
- Committing to environmental stewardship
- Securing the public trust through transparency and accountability
Why Resources?

**NASA Strategic Goals:**

- Extend and sustain human activities across the solar system
- Create the innovative new space technologies for our exploration, science, and economic future

**Affordable and Sustainable**

Critical for exploration beyond low Earth orbit
- Robotics & Automation
- Power Systems
- Propulsion
- Habitation & Life Support
- Space Resource Utilization
A New Level of Civilization
Where are the Resources?
**Resources**

### Possible Destinations
- **Moon**
- **Mars & Phobos**
- **Near Earth Asteroids & Extinct Comets**
- **Europa**
- **Titan**

### Common Resources
**Water**
- Moon
- Mars
- Comets
- Asteroids
- Europa
- Titan
- Triton
- Human Habitats

**Carbon**
- Mars (atm)
- Asteroids
- Comets
- Titan
- Human Habitats

**Metals & Oxides**
- Moon
- Mars
- Asteroids

**Helium-3**
- Moon
- Jupiter
- Saturn
- Uranus
- Neptune

### Core Building Blocks
- Atmosphere & Volatile Collection & Separation
- Regolith Processing to Extract O₂, Si, Metals
- Water & Carbon Dioxide Processing
- Fine-grained Regolith Excavation & Refining
- Drilling
- Volatile Furnaces & Fluidized Beds
- 0-g & Surface Cryogenic Liquefaction, Storage, & Transfer
- In-Situ Manufacture of Parts & Solar Cells

### Core Technologies
- Microchannel Adsorption
- Constituent Freezing
- Molecular Sieves
- Hydrogen Reduction
- Carbothermal Reduction
- Molten Oxide Electrolysis
- Water Electrolysis
- CO₂ Electrolysis
- Sabatier Reactor
- RWGS Reactor
- Methane Reformer
- Microchannel Chem/thermal units
- Scoopers/buckets
- Conveyors/augers
- No fluid drilling
- Thermal/Microwave Heaters
- Heat Exchangers
- Liquid Vaporizers
- O₂ & Fuel Low Heatleak Tanks (0-g & reduced-g)
- O₂ Feed & Transfer Lines
- O₂/Fuel Couplings
Water on Earth

Oceans = 700 km Ø Sphere

Illustration by Jack Cook, Woods Hole Oceanographic Institution
Astronomers estimate that if Ceres were composed of 25 percent water, it may have more water than all the fresh water on Earth. Ceres' water, unlike Earth's, is expected to be in the form of water ice located in its mantle.
Comets & Asteroid
H$_2$O Resources

Ceres Telescope Image:
Dawn Mission to investigate in 2015!

NASA Deep Impact & Stardust
(Wild 2)

JAXA Hayabusa
25143 Itokawa

12
Europa, as viewed from NASA's Galileo spacecraft. Visible are plains of bright ice, cracks that run to the horizon, and dark patches that likely contain both ice and dirt. Image Credit: NASA
Mars H$_2$O Resources

Measured H$_2$O content in top ~ 1 m of Mars in 5x5 pixels (Rapp, 2008)

Water Snow on Viking 2 landing site in May, 1979 (NASA Photo ID 211093) 11. Viking scoop dug 15 cm while it is expected the ice-cemented ground is at 24 cm depth. (Zacny, 2012)
Moon H$_2$O Resources

<table>
<thead>
<tr>
<th>Depth (m) to Stable Ice (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
</tr>
</tbody>
</table>

Depth (m) to the 1 kg/m² per billion year ice loss isotherm, from [2]. White denotes stability within 1 cm of the surface, beige indicates stability below 1 m [3].
In a 1961 paper, Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice.

Apollo samples, 1969-1972 point to a bone dry Moon.
Our Evolving Understanding of the Moon and its Resources

Missions to the Moon in the 1990's provided intriguing data that suggested the permanently shadowed regions of the Moon may harbor water ice and other volatiles.

Clementine Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles.

Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice.

Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow.
Our Evolving Understanding of the Moon and its Resources

Conclusions drawn from Clementine and Lunar Prospector regarding lunar water ice was vigorously debated.

Planetary Scientist, Larry Taylor, says he will “eat his shorts if there is water on the moon.”

Clementine Bi-Static Radar suggests water ice in permanently shadowed regions near the poles.

Watson, Murray and Brown theorize that cold traps at the moon’s poles may contain water ice.

Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow.
Our Evolving Understanding of the Moon and its Resources

Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions.

- Synthetic Aperture Radar on Chandrayaan 1 returns data that is consistent with water ice in the PSR's.
- Clementine's Bi-Static Radar suggests water ice in permanently shadowed regions near the poles.
- Watson, Murray, and Brown theorize that cold traps at the moon's poles may contain water ice.
- LCROSS impacts Cabeus A and clearly detects significant quantities of water in the ejecta.
- Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow.
LCROSS & LRO Definitively Prove Existence of Volatiles at the Lunar Poles

Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

<table>
<thead>
<tr>
<th>Column Density (# m$^{-2}$)</th>
<th>Relative to H2O(g) (NIR spec only)</th>
<th>Concentration (%)</th>
<th>Long-term Vacuum Stability Temp (K)</th>
<th>UV/Vis</th>
<th>NIR</th>
<th>LAMP</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO</strong></td>
<td>1.7e13±1.5e11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>H$_2$O(g)</strong></td>
<td>5.1(1.4)E19</td>
<td>5.50</td>
<td>106</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H$_2$</strong></td>
<td>5.8e13±1.0e11</td>
<td>1.39</td>
<td>10</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>H$_2$S</strong></td>
<td>8.5(0.9)E18</td>
<td>0.92</td>
<td>47</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Ca</strong></td>
<td>3.3e12±1.3e10</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hg</strong></td>
<td>5.0e11±2.9e8</td>
<td>0.48</td>
<td>135</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>NH$_3$</strong></td>
<td>3.1(1.5)E18</td>
<td>0.33</td>
<td>63</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Mg</strong></td>
<td>1.3e12±5.3e9</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>SO$_2$</strong></td>
<td>1.6(0.4)E18</td>
<td>0.18</td>
<td>58</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>C$_2$H$_4$</strong></td>
<td>1.6(1.7)E18</td>
<td>0.17</td>
<td>~50</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>CO$_2$</strong></td>
<td>1.1(1.0)E18</td>
<td>0.12</td>
<td>50</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>CH$_3$OH</strong></td>
<td>7.8(42)E17</td>
<td>0.09</td>
<td>86</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>CH$_4$</strong></td>
<td>3.3(3.0)E17</td>
<td>0.04</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>OH</strong></td>
<td>1.7(0.4)E16</td>
<td>0.0002</td>
<td>&gt;300 K if adsorbed</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>H$_2$O (adsorb)</strong></td>
<td></td>
<td>0.001-0.002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Na</strong></td>
<td>1-2 kg</td>
<td></td>
<td>197</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>CS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NHCN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NH$_2$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Our Evolving Understanding of the Moon and its Resources

Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions.

Synthetic Aperture Radar on Chandrayaan 1 returns data that is consistent with water ice in the PSR's.

Clementine's Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles.

Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice.

LCROSS impacts Cabeus A and clearly detects significant quantities of water in the ejecta.

Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow.

Apollo samples point to a dry moon.
Importance of Lunar Volatiles as a Resource

- **Water is Life**
  - Oxygen to breath
  - Water to drink
  - Water for cooling systems
  - Water for radiation shielding
  - Water for plants

- **Volatiles can be used to manufacture propellant**
  - Water is an easy form for the transportation of hydrogen & oxygen
  - Water can be converted into hydrogen and oxygen using abundant solar power in orbit
  - Hydrogen & Oxygen can be liquefied in space and stored in propellant depot
  - Orbital depots open up a commercial market for propellants
  - Alternatively, the hydrogen from the water can be combined with plentiful carbon monoxide to make methane, another useful propellant.

- Harvesting resources at our destinations can dramatically change the our mission architectures.
Propellant from the Moon will revolutionize our current space transportation approach

What if lunar lander was refueled on the Moon's surface?
73% of Apollo mass (2,160 tons)

Assume refueling at L1 and on Moon: 34% of mass (1,004 tons)

Assume refueling at LEO, L1 and on Moon:
12% of mass (355 tons)

+Reusable lander (268 tons)
+Reusable upper stage & lander (119 tons)

B. Blair, et. al., Space Resource Roundtable VI, November 2004
What’s the Next Step?

- We now know with certainty that there are volatiles at one spot on the moon.
- Comparisons of orbital instrument data with the LCROSS plume seem to suggest that the water is not evenly distributed.
- Until we know the distribution and accessibility of the volatiles don’t really know if we have a usable resource.
- A “Ground Truth” surface mission is the next logical step.
- RESOLVE is the payload that NASA and the CSA are designing to answer these questions.
RESOLVE Integrated with CSA Rover

470mm Length
533mm Width
746mm Height

Slide-in installation of RESOLVE platform To CSA Rover
RESOLVE Integrated with CSA Rover

Actual Photo on Mauna Kea
RESOLVE Mission Options – Potential South Pole Landing Sites

Neutron Depletion

LCROSS impact site

Dark blue represent the areas of highest neutron suppression

Circles A, B & C selected for closer examination
RESOLVE Mission Options – Potential South Pole Landing Sites

Depth to Stable Ice (m)
RESOLVE Mission Options –
Potential South Pole Landing Sites

Slopes at 250 m Scale (deg)
RESOLVE Mission Options – Potential South Pole Landing Sites

Maximum Days of Sunlight Using LOLA DEM

- A
- B

Kilometers

Kilometers

15
10
5
0
-100 -50 0
RESOLVE Mission Options – Potential South Pole Landing Sites

Cabeus Example (Site A)

LCROSS Impact Site

~10 km

LRO LROC WAC mosaic
Sun and Shadow Ops

**SUN (2.5 days)**
- Checkout
  - 6.17 hrs

  - **1st Navigation** 0.6 km
    - 3.88 hrs, 0.6 km total
  - Drill 1st Hole 4.33 hrs
    - Two 0.5m Augers (1-2)
    - One 1.0m Core (1)
  - Process Segments (1-8)
    - 8 segments, 26.84 hrs

  - **2nd Navigation** 0.6 km
    - 3.88 hrs, 1.2 km total
  - Drill 2nd Hole 4.33 hrs
    - Two 0.5m Augers (3-4)
    - One 1.0m Core (2)
  - Process Segments (9-10)
    - 2 segments, 9.59 hrs

**SHADOW (2 days)**
- Hibernate
  - 48 hrs

  - Consider using this "down time" to downlink detailed RESOLVE data (pics, detailed plant data, etc.)

**SUN (5 days)**
- Battery Recharge
  - 6.8 hrs

  - 3rd Navigate 0.6 km
    - 3.88 hrs, 1.8 km total
  - Drill 3rd Hole 4.33 hrs
    - Two 0.5m Augers (5-6)
    - One 1.0m Core (3)
  - Process Segments (11-15)
    - 5 segments, 19.85 hrs
    - 1st H2 Reduction

  - 4th Navigate 0.2 km
    - 2.29 hrs, 2.0 km total
  - Drill 4th Hole 4.33 hrs
    - Two 0.5m Augers (7-8)
    - One 1.0m Core (4)
  - Process Segments (16-20)
    - 5 segments, 19.85 hrs
    - 2nd H2 Reduction

  - 5th Navigate 1.0 km
    - 5.47 hrs, 3.0 km total
  - Drill 5th Hole 4.33 hrs
    - Two 0.5m Augers (9-10)
    - One 1.0m Core (5)
  - Process Segments (21-25)
    - 5 segments, 18.41 hrs
    - 3rd H2 Reduction

---

**MISSION SUMMARY**
- **Mission Length** 9.5 days
  - 2.5 days Sun
  - 2.0 days Shadow
  - 5.0 days Sun
  - 8.2 days of Scheduled Activities
  - 1.3 days of Reserve Time
- **Samples Processed**
  - 25 processed at 150 deg C
  - 3 processed at 900 deg C
- **Navigation**
  - 5 navigation periods
  - Distance traveled is 3.0 km
- **Drilling**
  - Ten 0.5m Augers
  - Five 1.0m Cores
Time & Energy by Mission Function

2.5 days Sun, 2 days Shadow, 5 days Sun

### Mission Time (hr)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hr)</th>
<th>Energy (W-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/O</td>
<td>6.17</td>
<td>684.77</td>
</tr>
<tr>
<td>Rover Translation</td>
<td>11.90</td>
<td>1754.76</td>
</tr>
<tr>
<td>Hot spot rovGng</td>
<td>7.50</td>
<td>1105.50</td>
</tr>
<tr>
<td>Using NGR</td>
<td>10.00</td>
<td>1765.00</td>
</tr>
<tr>
<td>Drilling/Changing Drill Bits</td>
<td>11.65</td>
<td>2056.23</td>
</tr>
<tr>
<td>Sample Manipulation</td>
<td>24.01</td>
<td>3620.82</td>
</tr>
<tr>
<td>Heat/Process Sample</td>
<td>70.53</td>
<td>20603.69</td>
</tr>
<tr>
<td>Cooldown</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Hibernate</td>
<td>48.00</td>
<td>3024.00</td>
</tr>
<tr>
<td>Recharge</td>
<td>6.81</td>
<td>429.21</td>
</tr>
<tr>
<td><strong>Sum (hrs)</strong></td>
<td><strong>196.57</strong></td>
<td><strong>35043.97</strong></td>
</tr>
<tr>
<td><strong>Sum (days)</strong></td>
<td><strong>8.190567</strong></td>
<td>****</td>
</tr>
</tbody>
</table>

### Mission Energy (W-hr)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Energy (W-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/O</td>
<td>684.77</td>
</tr>
<tr>
<td>Rover Translation</td>
<td>1754.76</td>
</tr>
<tr>
<td>Hot spot rovGng</td>
<td>1105.50</td>
</tr>
<tr>
<td>Using NGR</td>
<td>1765.00</td>
</tr>
<tr>
<td>Drilling/Changing Drill Bits</td>
<td>2056.23</td>
</tr>
<tr>
<td>Sample Manipulation</td>
<td>3620.82</td>
</tr>
<tr>
<td>Heat/Process Sample</td>
<td>20603.69</td>
</tr>
<tr>
<td>Cooldown</td>
<td>0.00</td>
</tr>
<tr>
<td>Hibernate</td>
<td>3024.00</td>
</tr>
<tr>
<td>Recharge</td>
<td>429.21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35043.97</strong></td>
</tr>
</tbody>
</table>
### Time, Energy & Battery State of Charge by Segment

(2.5 days Sun, 2 days Shadow, 5 days Sun)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hr)</th>
<th>Energy (W-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/O</td>
<td>6.17</td>
<td>684.77</td>
</tr>
<tr>
<td>Nav 1</td>
<td>3.88</td>
<td>572.05</td>
</tr>
<tr>
<td>Drill 1</td>
<td>4.33</td>
<td>764.25</td>
</tr>
<tr>
<td>Process 1</td>
<td>26.84</td>
<td>6831.09</td>
</tr>
<tr>
<td>Nav 2</td>
<td>3.88</td>
<td>572.05</td>
</tr>
<tr>
<td>Drill 2</td>
<td>4.33</td>
<td>764.25</td>
</tr>
<tr>
<td>Process 2</td>
<td>9.59</td>
<td>2142.65</td>
</tr>
<tr>
<td>Hibernate + Recharge</td>
<td>54.81</td>
<td>3453.21</td>
</tr>
<tr>
<td>Nav 3</td>
<td>3.88</td>
<td>572.05</td>
</tr>
<tr>
<td>Drill 3</td>
<td>4.33</td>
<td>764.25</td>
</tr>
<tr>
<td>Process 3</td>
<td>19.85</td>
<td>5156.07</td>
</tr>
<tr>
<td>Nav 4</td>
<td>2.29</td>
<td>338.08</td>
</tr>
<tr>
<td>Drill 4</td>
<td>4.33</td>
<td>764.25</td>
</tr>
<tr>
<td>Process 4</td>
<td>19.85</td>
<td>5156.07</td>
</tr>
<tr>
<td>Nav 5</td>
<td>5.47</td>
<td>806.02</td>
</tr>
<tr>
<td>Drill 5</td>
<td>4.33</td>
<td>764.25</td>
</tr>
<tr>
<td>Process 5</td>
<td>18.41</td>
<td>4938.63</td>
</tr>
<tr>
<td><strong>sum (hr)</strong></td>
<td>196.57</td>
<td>35043.97</td>
</tr>
<tr>
<td><strong>sum (days)</strong></td>
<td>8.190567</td>
<td></td>
</tr>
</tbody>
</table>

---

**Battery % Charge, 250W array, 3500 W-hr battery**
Notional Traverse Plan On Cabeus Floor

- Major waypoint
- Discovery: traverse re-plan
- Core Sample site
- Pre-planned traverse path
- Executed path

100 m radius landing ellipse

- 100 m
- 2 kilometers
The Path Forward

- RESOLVE and Rover Ground Demonstration Units (GDU) have completed their 90% design reviews and fabrication has begun.
- Flight software development is underway.
- Ground Development Units were used to conduct a mission simulation at a Lunar Analog Site (Mauna Kea, Hawaii) in the Summer of 2012.
- Flight Test Unit design began in 2012 after initial integrated tests of RESOLVE GDU.
- Goal is to have Flight Test Unit ready to go into thermal, vacuum and vibration testing.
- Hopefully, Commercial Lander capabilities will be coming on line in the 2014-15 timeframe due to the Google Lunar X-Prize.
### Sun&Shadow Solar/Battery Rover Architecture

**Version 2.1, 2011-6-23**

- **Destination:** Moon South Pole
- **Site:** Cabeus A1
  - Latitude: -85.75 deg
  - Longitude: -45 deg
- **Surface Mission Duration:** 9.5 days (7.5 w/ sun)
- **Primary Spacecraft:** Rover
- **Power Strategy:** Solar PV + Battery
  - Solar Array
  - Secondary Battery
    - 250 We
    - 3500 W-hr
- **Comm. Strategy:** Direct via McMurdo/Troll
- **Survey Track:** 3,000 m
- **Payload:**
  - Drill: 5x1m core, 10x0.5m auger
  - ISRU Reactor: 25@150C, 3@900C ISRU
  - Gas Chrom. / Mass Spec.: 25 samples
  - Neutron Spectrometer: 3000m
  - Near-IR Spectrometer: 3000m, 10 auger cuttings
- **Mission Energy:** 48,500 W-hr available
- **Mission Ave. Power:** 178 W predicted
- **Payload Mass:** 72 kg
- **Rover+P/L Mass:** 243 kg
- **Landed Mass:** 1285 kg
- **Wet Mass @ TLI:** 3,476 kg
- **Launch Vehicle Class:** Atlas V 411

---

**Field Testing Rover Prototype**

LPNS Epithermal ct/s (h=30 km)

**Cabeus South Pole Landing Site**
Space Resource Life Cycle

Resource & Site Characterization

Regolith Excavation

Site Preparation
(roads, pads, berms, etc.)

Mobile Transport of Oxygen

Habitats & Shelters

Oxygen & fuel for life support, fuel cells, & propulsion

Surface Mobility Assets

Power Source (Solar Array or Nuclear Reactor)

Regolith Transport

Hoppers & Ascent Vehicles

Polar Volatile Extraction

Regolith Processing

Construction feedstock

Mission consumables

Product Storage

(Modified LSAM Cargo Lander)

Power Generation

Manufacturing feedstock

Manufacturing & Repair

Surface Construction

Surface Construction

39
Surface scooping of the regolith is the easiest way to obtain $O_2$ through Hydrogen Reduction (1% yield), Carbothermal Reduction (12-14% Yield) or Molten Regolith Electrolysis (28% Yield).

Due to the stoichiometric ratio of H2 and O2 combustion, O2 is typically 85% of the mass required for propulsion.

If we want to have a fuel as well (H2, CH4), then we must mine the volatiles, which only exist in thermally stables regions below the regolith or in lunar crater cold traps at the poles.

Thermal models have shown that there may be water ice present in areas surrounding the craters at depths below 30 cm.

Mining robots must be able to scoop surface regolith for O2 ISRU.

Mining Robots must be able to dig below 30 cm for Volatiles ISRU including $H_2O$ and CH4.
Lunar Regolith Compaction

Regolith Densities (Lunar Sourcebook, LPI)

- Very Loose: 1.15 g/cm^3 - 1.22 g/cm^3
- Loose: 1.22 g/cm^3 - 1.32 g/cm^3
- Medium: 1.32 g/cm^3 - 1.51 g/cm^3
- Dense: 1.51 g/cm^3 - 1.68 g/cm^3
- Very Dense: 1.68 g/cm^3 - 1.82 g/cm^3

The top 25-30 cm of Lunar Regolith are Loose, below that is harder to excavate and mine.

Figure 1. VARIATION OF LUNAR REGOLITH BULK DENSITY WITH DEPTH.
The sectioned areas show the actual density variations and the smooth lines show the curve-fit given by Equation 1.9

The top 10 m of Lunar Regolith are fine grained.
The moon's axis of rotation is nearly perpendicular to the plane of its orbit around the sun, which casts long shadows off of crater rims and creates areas that never receive sunlight. These permanently shadowed regions (PSRs) have temperatures reaching below 90 K. At these temperatures, volatiles (including sulfur, carbon, hydrogen, hydrocarbons, and water ice) are stable there indefinitely.
PSRs Map

Legend
- Permanently Shadowed Regions

PSRs - Shackleton Crater

- Located at south pole
- 19-km diameter
- LRO data suggests up to 22% surface content is water ice
- Rim areas in sunlight most of the year
- Interior entirely in permanent shadow
- Rugged interior and steep walls

SOUTH POLE ILLUMINATION MAP
area extends from 88°S to 90°S [NASA/GSFC/ARIZONA STATE UNIV].
PSRs - Shackleton Crater

SHACKLETON CRATER vs. GRAND CANYON

Shackleton Crater

68897 feet across
(21 km)

13,779 feet deep
(4.2 km)

Grand Canyon

4325 feet deep
(1.3 km)

IMAGE CREDIT: DR. DAVID KRING (USRA)
Extreme Access Required

22 km diameter at rim
2 km deep

Houston Skyline

35 degree slope

15 degree slope

Credit: Jerry Sanders, NASA JSC

Credit: MER Rover Opportunity, NASA JPL

Meteor Crater, Arizona, USA
PSRs – Cabeus Crater

- ~100-km diameter
- Site of LCROSS Centaur impact
- Significant areas of permanent shadow
- Estimated 5.6 mass% water ice

Overview of a portion of the Cabeus northern rim looking from the southwest. Credit: NASA/GSFC/AZ State Univ.
PSRs - Small Craters

- Hundreds of small (<15 km) craters with PSRs within 12 degrees of poles [Bussey et al., 2003]
- Mini-SAR instrument imaged 40 small craters with water ice, ranging in size from 2 to 15 km
- Contain estimated 600 million metric tons of water ice

NORTH POLE ILLUMINATION MAP
AREA EXTENDS FROM 88°S TO 90°N [NASA/GSFC/ARIZONA STATE UNIV.]
Take Away Points

• Solar System Resource Utilization is the key to expanding Civilization off Earth
• The Solar System has vast amounts of resources but they must be acquired and processed to be useful
• Asteroids have huge amounts of resources in the Asteroid Belt and NEA’s
• Lunar Poles are also showing remote sensing evidence of volatiles resources
• Accessing the PSR craters is extremely hard and harsh — survival is challenging
• New Technologies and methods are required
Terrestrial Robotic Mining

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor
Early Visionary Studies 1900-1980's
Lunar Surface Construction & Assembly Equipment Study
Planetary Surface Systems Office - NASA JSC

Mining Excavator/Loader, Lunar

Ripper/Excavator/Loader

Regolith Hauler, Lunar

Articulated Hauler

Human Spaceflight Architecture Team
Colorado School of Mines 2001 - 2011

Mike Duke Project

Paul van Susante Projects

SysRand NASA SBIR
Lockheed Martin Corp. Bucket Drum Excavator (BDE) prototype.
NASA Centennial Challenge
Regolith Excavation Competition Winner 2009

Paul's Robotics Centennial Challenges Winner,
Worcester Polytechnic Institute (WPI),
Worcester, Massachusetts

$500,000 Prize!
Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA JSC/KSC 2009
Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA 2009
ATHLETE Excavation,
NASA JPL: 2009 - 2011
Caterpillar 287C semi-autonomous Multi Terrain Loader
Pneumatic Excavation and Regolith Transport
Load, Haul, Dump Excavator

Small Bulldozer
Robotic Precursor Small Robotic Mining Systems
(<50 Kg) 2011-2013

NASA Kennedy Space Center Excavator.
Regolith Advanced Surface Systems Operations Robot (RASSOR)

69
### Regolith Excavation Mechanisms

All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and Lunabotics Mining Competitions (2010, 2011 & 2012)

<table>
<thead>
<tr>
<th>Regolith Excavation Mechanism</th>
<th># of machines employing excavation mechanism</th>
<th>Lunabotics 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bucket ladder (two chains)</td>
<td>29</td>
<td>10</td>
</tr>
<tr>
<td>Bucket belt</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Front End Loader</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Scraper</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Auger plus conveyor belt / impeller</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Backhoe</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Bucket ladder (one chain)</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Bucket wheel</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Bucket drum</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Claw / gripper scoop</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Drums with metal plates or brush (street sweeper)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bucket ladder (four chains)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Magnetic wheels with scraper</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Rotating tube/scoops entrance</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vertical auger</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Rotating Scoop</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
2010 Lunabotics Mining Competition Winner: Montana State University
"The Mule" Lunabot, from Bozeman, Montana

2011 Lunabotics On Site Mining Category Winner: Laurentian University
"Production" Lunabot, from Sudbury, Canada
2012 Lunabotics Mining Winners

U Alabama – Grand Prize

Iowa State U – On Site Mining Category
2013 Lunabotics Mining Winners

Iowa State U – 1st Place On Site Mining Category & Grand Prize

North Dakota – 2nd Place On Site Mining

Human Spaceflight Architecture Team
What is the Most Popular Winning Design the SWAM Best Lunabot Regolith Mining Design for the Moon??

2009: Paul's Robotics WPI

2010: Montana State U

2011: Laurentian University

2012: Iowa State U
Or are these designs better?

2012: Embry Riddle Daytona

2011: U North Dakota

2012: FAMU/ Florida State U

2012: Montana State U
Top Robotic Technical Challenges*

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non-cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi-modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

*NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al., 2010)
Top Space Mining Technical Challenges

- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications
Conclusions

- There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth.
- None of these resources can be exploited without the first necessary step of extra-terrestrial mining.
- The necessary technologies for tele-robotic and autonomous mining have not matured sufficiently yet.
- The current state of technology was assessed for terrestrial and extra-terrestrial mining and a taxonomy of robotic space mining mechanisms was presented which was based on current existing prototypes.
- Terrestrial and extra-terrestrial mining methods and technologies are on the cusp of massive changes towards automation and autonomy for economic and safety reasons.
- It is highly likely that these industries will benefit from mutual cooperation and technology transfer.