Using Microwaves for Extracting Water from the Moon

COMSOL Conference
October 9, 2009
Boston, MA

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Water is one of the Most Plentiful Compounds in the Universe

• Earth’s water came from comets early in its history.
• Mars has vast quantities of water not only at the poles but also at lower latitudes (>55°).
• Significant quantities of water are present on several moons of Jupiter (Europa, Ganymede, and Callisto), Saturn (Enceladus), and Neptune (Titan).
Chronology of “Water on the Moon”

1959, prior to Apollo, scientists **speculated** that there should be some residual **water on the moon** from cometary impacts.

**Apollo** found “**no water**”.

1994, the SDI-NASA **Clementine spacecraft** mapped the surface. **Microwave radio signals from South pole shadowed craters were consistent with the presence of water.**

1998 – **Prospector - Neutron Spectrometer** – high H concentrations at poles

September 2009 – water observed at diverse locations of moon

  - **Chandrayaan-1** - Moon Mineralogy Mapper (M3)
  - **Cassini** - Visual and Infrared Mapping Spectrometer (VIMS)
  - **EPOXI** spacecraft - High-Resolution Infrared Imaging Spectrometer

October 9, 2009 - Lunar CRater Observation and Sensing Satellite - **LCROSS**
1998 Lunar Prospector - Neutron Spectrometer scanned for hydrogen-rich minerals. Polar craters yielded neutron ratios which indicated hydrogen => H₂O

Average H₂O concentration ~2% → Theoretically approaching Billions of tons

http://www.thespacereview.com/article/740/2
THIS MORNING the Centaur upper stage impacted a permanently shadowed crater, Cabeus A near the south pole of the Moon.

Mission Objective - confirm the presence of water ice in a permanently shadowed crater at the Moon’s South Pole.

Spectral analysis of the resulting impact plume will look for water ice.
Lunar CRater Observation and Sensing Satellite (LCROSS) – October 9, 2009

To Confirm the Presence of Water

- Mission Objective: Confirm the presence of water ice in a permanently shadowed crater at the Moon's South Pole.
- Projected lunar impact: October 9, 2009 at 11:30 UT (7:30 a.m. EDT +/- 30 min).

Today – This morning at 9 AM, LCROSS watched as the launch vehicle's Centaur upper stage impacted a permanently shadowed region near the south pole of the Moon.

Spectral analysis of the resulting impact plume will test preliminary findings by the Clementine mission which hinted that there may be water ice in the permanently shadowed regions.
Continuous Sunlight, Continuous Contact with Earth, “Moderate” Temperature, and Resources (water ice?)
Importance of Water

- Water (and oxygen) for the manned lunar outpost.
  Resupply requirements:
  1 ton water and 1 ton oxygen per year
  ~$10,000 to $100,000/ pound from Earth to moon
  Increasing to 10 tons per year

- Eventually (perhaps) - rocket propellant for exploration,
  Electrolyze water into H and O,
  liquify to LOX and LH
  10’s of tons not launched out of Earth’s gravitational well.
Water on the Moon

The water on the moon is in a number of different forms.

Chemically Bound water – Hydroxyl groups -OH
• The hydroxyls can be on the surface of the grains of soil.
• They can also be part of the chemical composition of the rock.
• This could include other hydrated chemical species (at the poles).
• Relatively small weight percent measured in Apollo soils.

Molecular water H2O
• Recently measured water vapor near the lunar surface.
• Water molecules lightly bound to Si+ dipoles on the surface of grains of lunar soil.
• Water ice physically condensed at poles. This physically condensed cryogenically trapped water ice is speculated to be present in relatively high concentrations (on the order of 2 weight percent),
This is the water we have proposed to extract with microwaves.
Use of Microwaves for the Extraction of Lunar Water

- Lunar Soil (in vacuum) is a Super Thermal Insulator. It is like an aerogel, very low heat flow.

- Microwave energy penetrates the soil heating from the inside out. Penetration depth is dependent on Frequency and dielectric properties.

- Conversion from electricity through microwaves to heat, efficient, heating causes sublimation of water ice.

- Excavation may not be required. Cryogenic water ice is as hard as granite. Saving energy, infrastructure, and equipment. Little if any disruption of lunar dust (hazard).
“Moon in a Bottle”
Laboratory Proof of Principle

Fused silica vessel with lunar permafrost simulant.
Experimental Facilities

- Standardized lunar regolith simulant (JSC-1A), particle size distribution and chemistry of (Apollo 14).
- Water ice concentration (2 weight %, 2g)
- Temperature (-196 to –50°C), LN2,
- Vacuum level (10-5 torr),

Bench top microwave facility
A. Vacuum quartz lunar regolith simulant vessel
B. Liquid nitrogen cold-trap
C. Turbo-molecular vacuum pump
D. LN2-cooled regolith simulant
E. Microwave oven chamber
Extraction Efficiency

- Microwaves coupled well to soil simulant at LN2 temperature.

- The regolith and the cold trap were weighed before and after the experiment.

- At least 95% of the water added to the regolith simulant was extracted (in 2 minutes) all below 0°C.

- Of the extracted water 99% was captured in the remote cold trap.
Microwave Lunar Water Extraction Prototype

- Magnetron source (2.45 GHz, 1100 W) with isolator, auto-tuner and copper high-gain horn.
- Mounting provides mobility over surface and height adjustment of horn.
- Temperatures within the bed of simulant (JSC-1A) were made using fiber optic temperature sensor in place during heating.

- Vacuum chamber evaluation of the microwave penetration and water vapor permeability through lunar soil simulant.
### Penetration Depth

\[ \text{Penetration} \sim \frac{\lambda (\varepsilon')^{1/2}}{2 \pi \varepsilon''} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>(\varepsilon'')</th>
<th>(\varepsilon')</th>
<th>Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.1</td>
<td>8</td>
<td>6cm</td>
</tr>
<tr>
<td>Simulant JSC-1</td>
<td>0.1</td>
<td>4</td>
<td>10cm</td>
</tr>
<tr>
<td>Ice</td>
<td>0.001</td>
<td>3</td>
<td>1m</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.0001</td>
<td>2</td>
<td>100m</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.00001</td>
<td>3</td>
<td>1000m</td>
</tr>
</tbody>
</table>

\[ \varepsilon = \varepsilon' + j \varepsilon'' \]

- \(\varepsilon'\) dielectric constant
- \(\varepsilon''\) loss factor

*1/e (0.37) of the original value.
Dielectric Property Measurements
Lunar Soil Simulant – JSC-1A

With Frank Hepburn - EM20

• Our custom fabricated 10 GHz (range 8 – 12 GHz) X-band waveguide apparatus for dielectric measurements over a range of temperatures, LN₂ to above room temperature.
• Heating coils near the coax connectors (not shown) keep the instrument connections at room temperature while the sample residing between the cooling the coil is chilled with free-flowing LN₂.
Dielectric Properties of JSC-1A Simulant
X-band 10 GHz, room temperature

Real and imaginary
1. Electric Permittivity (dielectric constant & Loss factor) and
2. Magnetic Permeability

We expect that Nano-phase Fe in lunar soil will significantly affect the permeability.

Proposal pending: Loan of Apollo Soil sample to measure dielectric properties.
Temperature Dependence (-73C to 63C) of the Dielectric Properties of Lunar Soil Simulant JSC-1A

Dielectric constant (real component of permittivity) vs. frequency over the X-band (8 to 12 GHz) for JSC-1A, temperatures from 63 C to -73 C.

The loss factor (imaginary part of permittivity) vs. frequency 8 to 12 GHz 63 to –73 C.
COMSOL - RF Module – Electromagnetic Waves – Harmonic Propagation

Lunar Soil Simulant Dielectric Properties

Subdomain Settings

Electric Permittivity
4 - 0.1j

Magnetic Permeability
1 - 0.0j

COMSOL 3.5a
Geometry - Draw

Rectangular Microwave Source

Cubic Meter Cavity Filled With Lunar Soil Simulant
Boundary Conditions

- Port
- Rectangular Port
- Perfect Electric Conductor
- Continuity
- Scattering Boundary

Port Power: 10 Watt
Meshing must satisfy the Nyquist criteria

Maximum element size \[= \frac{c}{\lambda}/2.5\]
\[= \frac{3e8}{2.45e9}/2.5\]
Microwave flanges for the three different microwave frequencies (0.9 GHz, 2.45 GHz and 10 GHz) used in this project showing the relative sizes of the experimental and test measurement hardware. Their standard sizes are designated WR975, WR340 and WR90 respectively. Each microwave frequency requires different geometry for COMSOL.
RFW - Total Energy Density
Iso-Surface
Penetration into Simulant

2.45 GHz
0.5 GHz
10 GHz
Steady-State Electromagnetism Coupled with Heat Transfer by Conduction

2.45 GHz
1 KW power
Temperatures to 5000K
RFW coupled with Heat Conduction - Transient Temperature Isotherms, 10 hours
Click to start animation
RFW coupled with Heat Conduction - Transient Temperature Isotherms, 10 hours
Application of COMSOL

- Processing parameters and hardware requirements for water extraction is a complex multi-physics problem.

- Microwave coupling to materials and heating is dependent on frequency and materials properties.

- Materials properties are a function of frequency and temperature.

- Can calculate microwave penetration and heating, with frequency and temperature dependent lunar soil dielectric properties.

- To Do – Model the Percolation of water vapor through the soil (porous media) characterized by the Darcy constant (currently being measured by Southern Research Institute).

- Parametric modeling will permit the evaluation of processing parameters most suitable for prototype hardware development, testing, and trade studies.
Acknowledgements:

NASA HQ – Joint Science Mission Directorate (SMD) & Exploration Technology Development Program (ETDP) Lunar Advanced Science and Exploration Research (LASER) program

MSFC Management – Prior Seed Funding

Co-Investigators:

Dr. William Kaukler – University of Alabama-Huntsville
  Hardware Instrumentation
  Dielectric Property Test Configurations

Frank Hepburn – Materials & Processes, MSFC-NASA
  Dielectric Property Measurements - Network Analyzer

COMSOL – Walter Frei - Technical assistance with the models

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