
How an HEOMD/AES ISRU-focused robotic mission offers cross-cutting science relevance for polar volatiles

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NAS/NRC report, “*Scientific Context for the Exploration of the Moon*” identified these goals for the lunar poles:

- **Science Goal 4a**—Determine the *compositional* state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.
- **Science Goal 4b**—Determine the *source(s)* for lunar polar volatiles.
- **Science Goal 4c**—Understand the *transport, retention, alteration,* and *loss processes* that operate on volatile materials at permanently shaded lunar regions.
- **Science Goal 4d**—Understand the *physical properties* of the extremely cold (and possibly volatile rich) polar regolith.
- **Science Goal 4e**—Determine what the cold polar regolith reveals about the ancient solar environment.
Relevant NRC Reports: *Visions & Voyages Decadal Study*

*Decadal Study* posed these questions about lunar polar volatiles:

1. What is the lateral and vertical distribution of the volatile deposits?
2. What is the chemical composition and variability of polar volatiles?
3. What is the isotopic composition of the volatiles?
4. What is the physical form of the volatiles?
5. What is the rate of the current volatile deposition?
Resource Prospector’s Tool Box

Mobility
Rover
- Mobility system
- Cameras
- Surface interaction

Prospecting
Neutron Spectrometer System (NSS)
- Water-equivalent hydrogen > 0.5 wt% down to 1 meter depth

NIR Volatiles Spectrometer System (NIRVSS)
- Surface H₂O/OH identification
- Near-subsurface sample characterization
- Drill site imaging
- Drill site temperatures

Sampling
Drill/Sample Acquisition
- Subsurface sample acquisition
- Auger for fast subsurface assay
- Sample transfer for detailed subsurface assay

Processing & Analysis (WAVE)
Oxygen & Volatile Extraction Node (OVEN)
- Volatile Content/Oxygen Extraction by warming
- Total sample mass

Lunar Advanced Volatile Analysis (LAVA)
- Analytical volatile identification and quantification in delivered sample with GC/MS
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU
RP Payload – Neutron Spectrometer System (NSS)

NSS (NASA ARC/Lockheed Martin ATC)

Selected Requirements

• Measure neutron fluxes consistent with $\geq 0.5$ wt% Water Equivalent Hydrogen (WEH) abundance above ambient WEH abundance, while roving at 10 cm/sec.

• Measure neutron fluxes consistent with $\geq 0.5$ wt% WEH abundance, buried under as much as 100 cm of dry regolith, while stationary for $\geq 120$ sec.

• Surface field of view: full width at half maximum (FWHM) between 50 cm and 150 cm along the traverse path.

Lab and Field Testing

• Environmental testing – random vibe/acoustic and TVAC, 2014

• Deployed on Mojave Volatiles Prospector/KREX2 rover in field, 2014

• Deployed on RP15 rover field testing in JSC, 2015.

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Integrated NSS ETU-1 on RP15 Rover Testbed (2015)

**Instrument Name** | **Neutron Spectrometer**
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**Source** | ARC/Lockheed Martin ATC
**Primary Functions** | Hydrogen concentration to depth of 100 cm
**TRL** | 6
**Mass [kg]** | 1.6
**Dimensions [cm]** | Sensor Module: 21.3 x 32.1 x 6.8
 | Data Processing Module: 13.9 x 18.0 x 3.0
**Power [W]** | 1.5
**Sensitivity** | WEH to ≥0.5 wt% water-equivalent at 10 cm/s
**Accuracy** | 5 – 10% absolute

Dark desert pavements have higher “water” abundance due to clays in subsurface
Key RP Measurement Goals

- Detect presence of H$_2$O/OH on the surface while roving and in subsurface drill cuttings
- Quantify concentration of water ice ≥ 0.5%
- Measure mineralogy while roving and in subsurface drill cuttings
- Image the spectrometer FOV while roving (context) and in multiple colors when stopped, and pre-, post-drilling
- Measure the spectrometer FOV temperature (LCS) while roving and drilling

Instrument Testing

- Full environmental testing (e.g., random vibe, thermal vac)
- GRC TVAC Testing: Testing with Drill into water-doped lunar simulant as cold as -160°C (113K).
- Field Testing: Mojave (Mojave Volatiles Prospector), Hawaii (RESOLVE 2012, BASALT), JSC Rock Yard (RP15)
RP Payload - NIRVSS

GRC TVAC Drill Testing

DOC Composite 410, 740, 905nm

ARC Rock Yard Prior to MVP Deployment
NIRVSS Real-time Band Depth Mapping

DOC Context Imaging While Roving

Spectra of Cuttings in each 10cm “Bite”

LCS Temperature measurements while roving during RP15 testing
**Drill/Sample Acquisition (Honeybee Robotics)**

**Selected Requirements**

- Acquire and transfer a minimum of 12 cc, from a minimum 4 cm section (bite) of lunar regolith sample ... to the OVEN subsystem, from a depth down to 100 cm
- Expose augered cuttings for inspection by NIRVSS from 8 different locations, down to 100 cm depth.
- Measure the subsurface temperature down to 100 cm.
- Drill a minimum of 18 holes to 100 cm depth.
- Measure the strength of the lunar regolith within ±10 MPa (TBR)

**Testing at GRC VF13 Vacuum Facility**

- Delivered sample to crucibles from 22 different locations from 40 cm depth (4 separate tests)
- Vacuum level: < 1x10^{-5} torr
- Ambient Temperature: -90° C to -50° C
- Regolith Temperature: < -100° C
### Instrument Name: Drill

<table>
<thead>
<tr>
<th>Source</th>
<th>Honeybee Robotics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Functions</td>
<td>Subsurface sample acquisition/transfer, thermal and geotechnical data of regolith</td>
</tr>
<tr>
<td>TRL</td>
<td>6</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>14.75 CBE</td>
</tr>
<tr>
<td>Dimensions (stowed) [cm]</td>
<td>27.1 x 21.5 x 177</td>
</tr>
<tr>
<td>Telemetry (while operating)</td>
<td>~3.4 kbits/s</td>
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</table>

#### Integrated Drill Testing on RP15 Rover Testbed

![Image of the Drill on the Rover Testbed](image)

*Sample Tube*
Water Analysis and Volatile Extraction (WAVE)

History
- Initial concept development through STMD as part of the RESOLVE Payload
- Mass Spectrometer developed through SBIR

Components
- **Mass Spectrometer:** Inficon Quadrupole mass spectrometer, 2-70 AMU, 6 Hz sampling rate
- **Gas Chromatograph:** Inficon Fusion MicroGC module, Single Plot-Q column (8m), separate inert components from CO₂ and H₂O
- **Sample Handling / Oven:** Receives sample, weighs sample, heats to 150°, 350° and 450° C, multiple, reusable crucibles
**Key RP Measurement Goals**

- Determine the volatile concentration in subsurface samples
- The Oven accepts up to 15g of sample (key to retain volatiles)
- Measure water vapor from Oven to <1000 ppm (equivalent to <0.1% water ice in regolith sample if only water present)
- Measures spectrum from 2-70 AMU
- Will measure isotopes including D/H and $^{18}\text{O}/^{16}\text{O}$

**Instrument Testing**

- Full environmental testing (e.g., random vibe, thermal vac)
- Oven and GC subsystems integrated into RP15 Field Testing
- Oven subsystem integrated into GRC Drill Testing (Spring 2017)
RP Payload – WAVE: Chemical and Isotopic Composition

WAVE Testing on RP15 Rover During JSC Rock-Garden Testing

GC/MS Spectrum of Air

LAVA GC User Interface

Increasing water peak as water evolves from heated OVEN sample

Isotopes

H₂¹⁶O

H₂¹⁸O
<table>
<thead>
<tr>
<th>Science Objective (priority)</th>
<th>LPVE Payload (priority)</th>
<th>RP Payload</th>
<th>TRL</th>
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</thead>
<tbody>
<tr>
<td>Determine form and species of volatile compounds at lunar poles (1)</td>
<td>Drill (1), borehole camera (1), sample acquisition and GCMS (1)</td>
<td>Drill (extraction of cuttings); NIRVSS (multi-color imaging; near-IR spectroscopy); WAVE (GCMS)</td>
<td>6, 5/6, 5</td>
</tr>
<tr>
<td>Determine vertical distribution and concentration of volatile compounds in lunar polar regolith (1)</td>
<td>Borehole neutron spectrometer (1), ground-penetrating radar (2)</td>
<td>Drill (extraction of cuttings from multiple depths), NIRVSS (multi-color imaging, near-IR spectroscopy), WAVE (GCMS)</td>
<td>6, 5/6, 5</td>
</tr>
<tr>
<td>Determine lateral distribution/concentration of volatile compounds in lunar polar regolith (1)</td>
<td>Rover-borne neutron spectrometer (1), ground-penetrating radar (2), surface imaging (2)</td>
<td>NSS (Rover-borne neutron spectrometer), NIRVSS (near-IR spectrometer surface measurements during prospecting)</td>
<td>6, 5/6</td>
</tr>
<tr>
<td>Determine the secondary alteration mineralogy of the regolith (2)</td>
<td>X-ray diffraction (2)</td>
<td>NIRVSS (Near-IR spectroscopy and multi-color imagery of regolith)</td>
<td>5/6</td>
</tr>
<tr>
<td>Determine composition and variation in lunar exosphere adjacent to the cold traps (2)</td>
<td>Exosospheric mass spectrometer (2)</td>
<td>Not directly addressed.</td>
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### SCEM Science Goal

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<th>RP Payload</th>
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<tr>
<td>4a - Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.</td>
<td><strong>Drill</strong> cuttings; <strong>WAVE</strong> (GCMS) analysis of surface and subsurface volatiles provides chemical and isotopic composition; <strong>NIRVSS</strong> provides mineralogy; <strong>NSS</strong> provides lateral and approximate depth distribution; <strong>NIRVSS</strong> spectra of extracted drill cuttings provides vertical distribution, as does <strong>WAVE</strong> analysis of samples from depth</td>
</tr>
<tr>
<td>4b - Determine the source(s) for lunar polar volatiles.</td>
<td><strong>WAVE</strong>: Chemical and isotopic composition point to sources; <strong>NIRVSS</strong>: imagery of physical state and NIR spectra inform emplacement mechanism.</td>
</tr>
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<td>4c - Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions</td>
<td>Drilling/sampling within PSRs: <strong>WAVE</strong> chemical and isotopic composition reveal likely sources; <strong>NIRVSS</strong> imagery of physical state and spectra inform emplacement mechanism.</td>
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<td>4d - Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith.</td>
<td><strong>Rover</strong> slip vs slope, <strong>Drill</strong> penetration force and augering torque with depth, and imaged rover wheel/surface interaction provide geotechnical info</td>
</tr>
<tr>
<td>4e - Determine what the cold polar regolith reveals about the ancient solar environment.</td>
<td>Not directly addressed.</td>
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• Define the composition, form, and extent of the volatile resources
• Characterize the environment in which the resources are found
• Define the accessibility/extractability of the resources
• Traverse several kilometers and sample and determine lateral and vertical distribution on meter scales
• Quantify the geotechnical properties of the lunar regolith in the areas where resources are found
• Identify resource-rich sites for targeting future missions
Backup Slides