Resource Prospector (RP)

The Mission & Project

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No Export Controlled materials (ITAR/EAR)
(New RP mission animation here)
Where RP fits in the Marketplace…

Goals:

Orbital Observations → Orbital Prospecting → Ground Truthing → Ground Prospecting → ISRU & Mining Assessment → Mining Demonstrations → Bulk Production

Missions:

Clementine
Lunar Prospector
LCROSS
LRO

Resource Prospector (RP)

Industry
Industry

RP bridges Government and Industry volatiles questions, key to determining Economic viability and Agency potential of the Moon

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How RP was cast

The RP team was formed with the goal of applying low-cost, risk-tolerant learning, on a larger mission scale.

Specifically, RP was built on the learning of the LCROSS & LADEE missions

- LCROSS cost $79M (sans LV) and helped to rewrite the books on the moon
- ESMD AA Scott “Doc” Horowitz selected LCROSS from 19 proposals, noting:

  "While this is a Class D mission, I suspect there is learning that will come from LCROSS that will be applicable to even Class A missions"

  "I could triple the cost to try to guarantee no failure, or I could do three projects and even if one fails, I still get more done"

- LADEE demonstrated balancing class D and class C approaches, tailoring classic NASA approaches with more risk-tolerant methods.
- Leadership of the LCROSS and LADEE lunar teams were joined with the ongoing RESOLVE ISRU team, and added a low-cost STMD mobility team to form an excellent, capabilities-driven NASA team
RP’s Class D/C Low-cost Tenets

**Key Management tenets:**
- RP is a nimble, responsive, cost-effective, requirements-focused mission; it’s not a typical NASA flight project.
- Create teams of non-conventional thinkers: Multi-experienced, multi-discipline who are dissatisfied with slow, big projects
- Leverage early-career folks who don’t know “it’ll never work” and mix them in with seasoned people
- Employ full-time team members for full engagement to the cause
- Streamline interactions with the institution.
  - I have met with the three Center directors to help align the institutional support. They are co-conspirators
  - Top-down institutional support is a must to help guide division and branch management to the cause, and move with alacrity

**Key Technical tenets:**
- Accept single-string design with limited or no redundancy; instead utilize functional backups
- Use off-the-shelf componentry; avoid new designs where possible; use commercially-available box-level components
- Avoid any design changes to an existing commercially available design
- Minimize complexity; minimize deployables and articulations
- Simple safe mode; launch power-off
- Accept the risk of minimum hardware spares
RP Adaptability

RP conceived when Agency was focused on Mars
- This meant lunar-RP needed international partnering to bring political value and defray costs

RP was in a continual state of adaptation based on partner needs!
- Canada to bring a rover, so RP steered the payload configuration to close the design
- Japan to bring a large lander, so RP had to entertain mass-reduction targets
- Taiwan to build the NASA lander, so RP had to help and consider instrument suite additions
- NASA to provide SLS LV, so RP had to chase new external constraints, including a crewed Orion(!)
- Commercial industry to provide landing services, so RP pathfinds a new WBS org structure

The RP team was always adapting to evolving Agency constructs, becoming a highly-effective, multi-Center team
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RP executed a “Mission in a year” project lifecycle! The team flowed-down requirements, executed gate reviews, designed and built real hardware, “flying the mission” in just 11-months.

NASA Office of Chief Engineer awarded RP the Systems Engineering Excellence Award (2017) for this novel activity (to a Phase A project!)

HEOMD/AES awarded RP with their Innovation Award

*RP15 delivered early and under budget!*
Current RP requirements flow from HEOMD Level-1 MRD reqs

- MRD requirements synopsis: *Land in a lunar polar region; characterize the surface/subsurface volatiles; demonstrate volatiles processing*
- RP Level-2 requirements flow-down considered a number of factors:
  - Low-cost approaches
  - Exploration & Science community interests (SKG’s, SCEM, etc)
  - Commercial interests
- RP requirements are very mature, well-researched and vetted
- From the requirements, RP evolved a Design Reference Mission (DRM)
  - This DRM evolved through the various partnering options (agile team)
  - This DRM uses mobility to characterize the challenging lunar polar region
  - Class D designation = cost savings within the design and test campaign
  - How long does the mission need to be to address the given requirements?

So does RP need to “make it through the lunar night” to meet L1 requirements?
RP making it through the lunar night

RP balanced capabilities & cost

- RP’s assessment: Level-1 requirements CAN be met in a single lunar day
  - This includes multiple visits to the four different Ice Stability Regions, enabling fully characterizing the nature of lunar polar volatiles (affirmed by LEAG\(^1\) and FOLNV\(^2\))

- RP tactically approached the rover design
  - Design for a single lunar day and save the taxpayer some money

- If multiple lunar days are required, RP would similarly adapt the design
  - RP has already found ways to extend the existing design to make it through 2-3 lunar nights

- Caution:
  - It is tempting to consider rover nuclear sources to eliminate solar power needs
  - RP performed analyses in the past for each ASRG\(^3\) and RHU\(^4\) sources and found:
    - Radioactive/Decay products can greatly interfere with neutron-sensing instrumentation
    - Radioactive emissions containment spends mass, complexity, cost, schedule, and risk
    - Launching radioactive manifests are a burden to the nascent commercial lander industry

This RP team can adapt to whatever requirements are passed-down

\(^1\) LEAG = Lunar Exploration Analysis Group
\(^2\) FOLNV = Friends of Lunar/NEO Volatiles
\(^3\) ASRG = Advanced Stirling Radioisotope Generator
\(^4\) RHU = Radioisotope Heater Unit
RP Partnering Strategies

RP working all the Partnering angles

International partnerships


Commercial partnerships

Phase A
- Formulating the RP payload-mobility system design

Phase A
- Build a "RP15" prototype rover/payload system ("Surface Segment")

Phase A
- "RP15" Surface Segment analogue and environmental testing

Phase B
- Investigate PPP option with SMD & STMD for Lunar Cargo services.

Phase B
- Craft acquisition SOW language and release for Lunar Cargo Services via RFP and BAA

Phase B
- Lock-down Surface Segment requirements while Commercial services are explored

Phase B
- TRL-advance key technologies and expand the RP driving simulator to enable Mission simulations

RP Surface Segment Timeline:

- FY14: Phase A (Formulation)
- FY15: Phase A (Demonstration: RP15)
- FY16: Phase A (Environmental testing: RP15)
- FY17: Phase B RPRC (Requirements baseline)
  - FY18: Phase B TRL Maturation and Mission Sims
  - FY19: Phase C: MDR/PDR (Implementation)
  - FY20: Phase C: CDR (Critical design)
  - FY21: Phase D: SIR/I&T
- FY22: RP launch (predicated by budget details)

7,165 line Integrated Master Schedule (IMS) available upon request
RP Independent Technical Reviews

- RP has held many independent technical peer reviews:
  - Payload Tiger Team Review (TTR)
  - Rover Tiger Team Review (TTR)
  - MOS/GDS Tiger Team Review (TTR)

Payload TTR Review:

- (9) TTR reviewers: GSFC (4) and ARC (5)
  - Excellent review, including MSL SAM suite comparison/contrast with lessons-learned: “If I did it again…”

Rover TTR Review:

- (8) TTR reviewers: JPL (3), GSFC (1), ARC (1), UoMaryland (1), UCF (1), UoOklahoma (1)
  - Excellent review, including rover trades & cost discussions: “Don’t start big and try to chip-away. Start with a Roomba and only add what you need”
• RP’s strategy is to decouple design advancement from the lunar cargo services partner
  – RP is pushing schedule toward “delivery to a shelf”

• 2017-07, RP “Requirements Checkpoint” (L2 SRR)
  – AES & NASA-ARC Chief Engineer’s office attend
  – Can pivot details once PPP better understood
  – Lander/SurfaceSegment ICD as simple as possible

• 2017-09, RP Payload SRR (L3 SRR for Rover)
  – AES & NASA-KSC Chief Engineer’s office attend

• 2018-01, RP Rover SRR (L3 SRR for Rover)
  – AES & NASA-JSC Chief Engineer’s office attend

• 2018-05, RP MOS SRR (L3 SRR for Rover)
  – AES & NASA-ARC Chief Engineer’s office to attend

• 2019-02 (TBR), RP “Requirements Checkpoint” (PDR for Surface Segment)
  – Contingent on funding levels and Agency decisions

RP Requirements Reviews
Significant progress in several key/unique areas towards TRL 6 by PDR

**Rover**
- Mobility controllers
- Mobility propulsion
- Mobility suspension
- Mobility steering
- Battery/BMS
- Dust Mitigation
- Localization software
- Slip detection software

**Payload**
- NSS
- NIRVSS
- TRIDENT
- WAVE

**MOS**
- Planning/Traverse/Mapping

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<th>TRL 4</th>
<th>TRL 5</th>
<th>TRL 6</th>
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The RP team built a fully functional Rover + Payload system to “fly” by the end of the FY.

This “RP15” rover has greatly accelerated the system design development maturity.
Past & Present Mars and Lunar Mobility Systems

RP15/RP1A

http://historicspacecraft.com/Probes_Mars.html

*includes instruments
RP Field Testing

NASA-ARC Mission Control room driving RP rover

Rover @ NASA-JSC Rock Yard from the rover (left) stereo camera

3-D Image Viewing of NIRVSS camera images during DOT

NASA-KSC Payload Control room (Firing Room 4)
RP Field Testing (video)
RP Field Testing (video)
Alternative locomotion for fluff

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Mobility, Lander Egress, Drilling
RP Environmental Testing

TVAC testing

TVAC chamber testing of RP15 rover and payload subsystems

RP15 wheels & steering assemblies undergoing TVAC test

OVEN system undergoing TVAC test
RP Environmental Testing (video)

Vibe testing

TVAC chamber Z-axis testing of RP15 rover

TVAC chamber X/Y-axes testing of RP15 rover

OVEN in vibe

Drill in vibe
Eight hours of radiation beam testing at BNL, testing rover and payload electronics

Discovered Single Event Upset and latch-up events which will inform our designs moving forward.
RP Technology Infusion from STMD or SBIR’s

WBS 4.0: Science
- STMD/NIAC Planning tool for Traverse Planning

WBS 5.0: Payload
- SBIR/Ph3 Honeybee Robotics drill (FY15/16/17)
- SBIR/Ph3 Virtual Machine Language with Blue Sun (FY16/FY17)
- SBIR/Ph2e and Ph3 NIRVSS AOTF Spectrometer Module with Brimrose (FY17)

WBS 6.01: Rover
- STMD/Georgia Tech: National Robotics Initiative. Studying RP rover “swimming” gait to optimize extracting a stuck rover
- STTR* Phase 2e: ProtoInnovations to study slip and rover embedding detection

* Small Business Technology Transfer (STTR).

Georgia Tech optimizing Rover swimming Gaits

Verve Driving Tool
RP Operational Model

Fully distributed operations

Operational locations same as development organization

The team that builds it, flies it
RP DIY Mission Ops!

- Build your own mission control center using the same software as the mission team. Follow the mission on your phone!

- Software is open source and community supported.

- Software in use on multiple missions: Jason 3, Mars 2020 testbed, MarCO, ASTERIA, IceSat 2, Landsat 9 instrument…

- Use pre-fab mission control displays on tablet, phone or computer OR build your own DIY control center

- Try our DIY Mission Control Prototype at: https://banner.ndc.nasa.gov
Community Engagement

- RP Community Workshop (July, 2015) prior to ESF – All day workshop open to all; cover all aspects of RP and had SSERVI Moderated Discussion in afternoon
- 2016 LPSC Microsymposium on Lunar / Mercury Volatiles (came out of the 2015 Workshop, organized by Jim Head and Anthony Colaprete)
- SSERVI: Several teams working directly with RP:
  - FINESSE (PI Heldmann): Use of NIRVSS in field studies
  - DREAM2 (PI Farrell): Lunar polar environments specific to RP (e.g., charging and plume exhaust impingement)
- LEAG, LPSC, AGU, etc since 2014
- RP Team members have published/presented more than 90 RP related abstracts/papers, with more than 5 peer reviewed publications since 2012
Understanding Lunar Water for Potential Utilization

- Moon now known to host all three forms of Solar System water (Endogenic, sequestered external and in-situ)*

- Do not yet understand the concentration, evolution and interrelated dynamics of these varied sources of water

- **Surface measurements across critical scales are critical to characterize the spatial distribution of water**

- Isotopic compositions will help pinpoint sources and sinks

- Combined with orbital data these observations will address the character and origin of water on the Moon and through the inner Solar System,

  **RP examines the lunar water cycle in an unprecedented way**

There is Water, But What is its Resource Potential?

- Data from LRO, LCROSS, M3 and other data sets suggest patchy and/or buried distributions of volatiles and potentially different reservoirs.
- Orbital observations limited to surface and/or low spatial resolution.
- Models predict near sub-surface temperatures in many sunlit areas are cold enough to retain water ice for geologic timescales.

...but how are volatiles distributed and accessed at the “human” level?

Hayne et al., 2015
Crater Mixing
- Dominant geological process affecting top meter of regolith is small impact cratering
- Distance between 10m wide craters (~1m deep) is ~50-150m
- Consequently top 0.5 meters is likely to be patchy at scales of 10s-100s of meters

Temperature Control
- Temperature appears to be a necessary requirement, but not the only determinant of volatile presence
- Thermal stability is defined as the temperature at which ice is stable in vacuum for geological periods of time (~Gyrs), or around <107K
- Temperature variations are largely determined by topography, thus temperature variations will be significant down to scales of <5 meters
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![Ice Stability Depth Map](Siegler and Paige, 2017)

Hurley et al. 2013
Measuring the Range of Possible Productivity

What is the ISRU value of deposits across the range of environments, terrain types and length scales?

Four environments defined based on the predicted thermal stability of ice with depth, the Resource Target Regions (RTRs):
- **Dry**: Temperatures in the top meter expected to be too warm for ice to be stable
- **Deep**: Ice expected to be stable between 50-100 cm of the surface
- **Shallow**: Ice expected to be stable within 50cm of surface
- **Surface**: Ice expected to be stable at the surface (i.e., within a Permanently Shadowed Region, PSR)

Is the Resource Need met in any of these RTRs?

Is one Resource Target Region better (e.g., more economical, safer) than another?
Key to Addressing the ISRU Potential

**Provide data for studies to the feasibility and economics of lunar resource utilization**

**Important Parameters for ISRU / Economic Models**
- Volatile distribution and form (concentration, including lateral and vertical extent and variability)
- Overburden: How much and type of material needing to be removed to get to ore?
- Working Environment: Sun/Shadow fraction, soil mechanics, trafficability, temperatures
- Tests theories of emplacement and retention that will improve models to predict ore location and grade (concentration)

**These Observations lead to Defining the Resource Reserves**
- Need data concerning distribution and accessibility to help determine if a resource and processing technique allows for positive Return on Investment (ROI), including Mass, Cost, Time, and Mission/Crew Safety
- Amount of product needed justifies investment in extraction and processing
- Provides data to Commercial entities to build business cases, direct investments and partnerships

From “Committee for Mineral Reserves and International Reporting Standards”, 2013
First Step in Mining is Exploration or “Prospecting”

- Need to provide strategic knowledge input to the resource potential / economics: In what environment is the ISRU potential (the Reserves) maximum?

Prospecting characterizes the location and the extent of the ore that is being sought

- Provides data for studies on the feasibility and economics to access the ore (ore = any material with potential economic or other value)

- Provides the ground truth and linkage between on-site conditions to regional remote sensing data sets

- Tests theories of emplacement and retention that will improve models, referred to in industry as a “Mineral Model” to predict ore location and grade (concentration)
Basis for Resource Need

Processing Assumptions:
• Distribution: 0.5% water ice with 0.5 meter dry over burden and 30% areal concentration, 20% uncertainty
• Excavation to 1m deep
• Capture efficiency: 10%, including concentration uncertainty, mining/acquisition, extraction, transportation, processing and storage

What reserves are required?

<table>
<thead>
<tr>
<th>Ice Concentration (wt%)</th>
<th>kg ice per m^3</th>
<th>kg ice minus uncertainty</th>
<th>Total Area Needed to 1 m deep, m^2</th>
<th>Min. Grid Scale (m)</th>
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<tr>
<td>0.25</td>
<td>2.5</td>
<td>2</td>
<td>18750</td>
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<tr>
<td>2</td>
<td>20</td>
<td>16</td>
<td>2344</td>
<td>48</td>
</tr>
</tbody>
</table>

Craters will leave an areal density of about 30% after 1Gyrs

From Hurley et al.
A. Need to measure the production fraction for a Need-equivalent volume (Ore Body)
   - What is the average water production from an Need-equivalent volume of ore?
   - The answer provides scales the production efficiency of a particular thermal region

B. Within a Need-equivalent volume what is the variability, or delineation of the ore deposit?
   - The answer informs the excavation technique and efficiency: Is the water patchy vs uniform at excavation tool scales? (the Areal Density)

C. What is the variability from one RTR to the next?
   - Answer informs regional production efficiency beyond a single sample site

A. Measure total yield of an ore body at scales sufficient to meet need

B. Delineation of the ore deposit across production area

C. Ore grade correlation with thermal environment across relevant geologic scales (>100m)
The mission must characterize an area sufficiently to evaluate the resource need

- Terrestrial mining companies have worked this problem since Lewis and Clark
- Harder for the Moon as the “Mineral Model” is very uncertain (one of the principle goals for RP is to define this model!)  
- Evaluated the required sampling using a series of Monte Carlo simulations with random distribution of water ice, sampled continuously, for example by a rover with a neutron spectrometer

Monte Carlo runs tested the uncertainty in sampling as a function of total distance or area coverage

- Sampled concentration was compared to “True concentration”, calculated for each run, and the error in sampling calculated (Error = \[\text{True – Sampled}/\text{True}\])
- Distribution of Errors provides likely (mean and median) uncertainty in a sampled
Monte Carlo Results for a 100 x 100 meter area

At a minimum need to traverse 180m with a RTR (Science Station) with a Goal of 320m
Subsurface Sampling Requirements

- Need to resolve gradients in ice vertical distribution to inform neutron measurements (down to at least 80cm)

- Subsurface sampling can be defined in terms of both sample size (e.g., “Drill Sample Segment” length) and the number of these samples obtained across the column

- Conducted Monte Carlo simulations of various Sample Segment Lengths and Sample Numbers

- Result: A Sample Length of >8cm and at least five samples per 80cm results in <10% integrated column uncertainty

- RP samples 10cm segments every 10cm to a depth of 100cm
Variograms – Identifying Spatial Distribution Scales

Measures spatial correlation: The geologic distance with respect to the Euclidian distance

- Beyond the “Sill” the lag value assumes no autocorrelation; beyond the longest geologic scale
- Different magnitudes of Sill indicate spatial structure scales
- Cratering model suggests measurements across scales of at least ~25-30 is necessary for 30% area fraction case
- Can calculate real-time with NSS and NIVRSS data, and later with drill data
A possible determinant of spatial scales is the depth to water ice stability
- This is essentially a measure of the spatial scales at which temperatures vary
- Gives an estimate of the distances over which measurements are necessary
- Used a validated 2+ lunar-day traverse (46 Earth days) to sample the depth-to-stable-ice across the 20m data product
- The four “runs” represent different origins from which the lag (distance between points) was calculated
- Several “Ranges” and “Sills” are clear, indicating several physical scales, with the largest being >600 meters
- Demonstrates that sampling across scales from 10s of meters to 100s of meters is required
How to determine the ore grade across a broad area?
• Drilling alone would require an unreasonable number of drill sites
• Measurements while driving give continuous sampling, however reflectance observations are only surficial, and neutron data can be ambiguous due to degeneracy in neutron energy and flux with concentration and burial depth

Boreholes used to tie-down neutron observations by constraining vertical profile
• A combined Drill / NIR Spectrometer or Drill / Sample Analysis system can measure the vertical destruction of water constraining neutron modeling – provides the “tie point” for the prospecting data
Resource Prospector – The 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)
  - NIR spectra from 1.3-3.8 μm
  - Near-subsurface sample characterization
  - Surface UV-NIR imaging
  - Surface temperatures

**Sampling**
- The Regolith and Ice Drill for Exploration of New Terrain (TRIDENT)
  - Subsurface sample acquisition
  - Auger for fast subsurface assay
  - Sample transfer for detailed subsurface assay

**Processing & Analysis**
- Water Analysis and Volatile Extraction (WAVE):
  - Optimized 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

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Prospecting builds the coverage density necessary to characterize a region and identifies points to drill/sample

- NSS and NIRVSS are on continuously, taking data while roving or parked
- Variations in neutron flux while roving identify abundance and burial depth of hydrogenous materials in subsurface
- Variations in NIR surface reflectance identify surface hydration, including bound hydroxyl (OH) and water, or frosts
- Both neutron and reflectance observations can be compared to continuous observations of surface temperature
Demonstrated real-time prospecting in the Mojave Desert using NSS and NIRVSS ETUs

Dark desert pavements have higher “water” abundance due to clays in subsurface.
Sampling via the TRIDENT and NIRVSS observes the vertical profile of water and other volatiles, tying down NSS derived concentrations

- TRIDENT samples in 10cm “bites” down to 1 meter, using a simple auger bit
- Each 10cm sample can be brushed to the surface for inspection by NIRVSS or delivered to a crucible in WAVE
- NIRVSS inspection identifies the presence of water and other volatiles in real-time, images the cuttings at multiple wavelengths and measures the scene temperature
- This process identifies the stratification of hydrogen bearing volatiles, “tying down” NSS measurements
Multiple tests on RP15 Rover and in FV13 TVAC at GRC demonstrated the TRIDENT and NIRVSS systems ability to capture samples at depth and identify water (at concentrations <0.25%) in real-time.

DOC Composite
410, 740, 905nm

Radiance

NIRVSS Spectra of cuttings piles

Water ice band depths calculated real time during VF13 testing

TRIDENT installed at VF13 TCAV facility
Sampling via the TRIDENT and NIRVSS observes the vertical profile of water and other volatiles, locking down NSS derived concentrations

- Any one of TRIDENT’s 10cm samples can be transferred to the WAVE furnace for processing
- The relatively large (15 grams) samples help to retain volatiles through the transfer and capture process
- Each sample is weighed then heated in steps to 450C, driving off gasses that are identified by the GC/MS
- Final “baked” samples are weighted again and the total absolute concentration of gasses determined
- This analysis provides an accurate concentration (%wt) of the water content in the soil
Analysis: Demonstration

TRIDENT delivery of samples to WAVE during RP15 Field Testing: From soil tube to OVEN through heating and analysis

RP15 Rover with TRIDENT and WAVE ETUS

OVEN Control Display

Water peak from evolved gas

WAVE analysis of room air

WAVE MS resolving water isotopes

GC Display

Isotopes

$H_2^{16}O$

$H_2^{18}O$
Good candidate polar landing sites meet these four criteria:
1. Surface/Subsurface Volatiles
2. Reasonable terrain for traverse
3. Direct view to Earth for communication
4. Sunlight for duration of mission for power
RP Traverse Modeling

Traverse Modelling

• Critical tool used to evaluate rover design, traverse timelines and measurement requirements
• Identified additional data sets and tools needed (e.g., Shape from Shadow DEMs, High-Resolution thermal modeling)
• Simulations now include synthetic lunar environment to evaluate “Speed Made Good” and real-time science operations

Planner Inputs / Constraints:

• Activity Dictionary (activities, durations, energy requirements)
• Waypoint Selection
• Power and Downlink Models (array size, efficiency, rover power, etc)
• Driving Speed (“speed made good”)
• Availability of sun and comm (time and space dependent)
• Trafficability (identify keep out areas of hazardous slopes)

In Traverse Video: Green = potential landing site, red=potential psr sample, grayscale=amt of sunlight, circles=drill sites
Traverse Modelling

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Virtual Mission Simulations

- Includes high-fidelity synthetic terrain down to 4cm
- A “Site Model” that includes hypothesized distributions of volatiles surface and subsurface temperatures, and other regolith properties
- Rover mechanics and power models
- Instrument models that react to the Site Model just as the instrument would on the Moon
- Allows tests of CONOPS, timelines, procedures, and measurement methods

In Traverse Video: Green = potential landing site, red=potential psr sample, grayscale=amt of sunlight, circles=drill sites
Hermite-A Region: Extended Mission Examples

Net no-sun days over 2.5 lunations (73 Earth days)
Traverse Example – Hermite A

NAC Mosaic

Ice Stability Depth Zones
red: PSR, green: 0-.5 m,
yellow: .5-1 m, gray: >1 m
1. Surface segment lands in high ‘net sun’ area.
2. Rover drives to nearby Resource Target Regions.
3. Rover returns to lander vicinity for long no-comm period containing short no-sun periods.
4. Rover drives again to Resource Target Regions.
5. Rover returns to lander again or ends mission in scientifically interesting area far from lander.
# Sample Multi-Lunar Day Traverse Summaries

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<th>Parameter</th>
<th>Option A</th>
<th>Option B</th>
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<td>87.75 N, 64.47 W</td>
<td>88.14 N, 67.24 W</td>
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<tr>
<td>Total Duration</td>
<td>46.5 days</td>
<td>46 days</td>
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<tr>
<td>Time without Comm</td>
<td>15 days</td>
<td>18 days</td>
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<tr>
<td>Distance Driven</td>
<td>6 km</td>
<td>3.3 km</td>
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<tr>
<td># Drilling Activities</td>
<td>36</td>
<td>40</td>
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<tr>
<td>Max sample separation</td>
<td>1.75 km</td>
<td>670 meters</td>
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<tr>
<td>End state</td>
<td>Potential short 3rd day*</td>
<td>3rd day unlikely</td>
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<tr>
<td>Lander mission opportunity</td>
<td>45 days w 2 x 24 h overnights, likely more*</td>
<td>45 days w 24 h overnight</td>
</tr>
</tbody>
</table>

These traverses used the current RP Rover design, with no optimization for night-survival

*Analysis of these regions was limited by span of calculated sun and comm maps
### RP’s Goals Align to High-Priority Science Goals

<table>
<thead>
<tr>
<th>RP Goals</th>
<th>SCEM</th>
<th>Decadal Survey (priority order)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine lateral and vertical distribution and extent of polar volatiles</td>
<td>4a - Determine the composition state (elemental, isotopic, mineralogical) and composition distribution (lateral and depth) of the volatile component in the lunar polar regions</td>
<td>Determine form and species of volatile compounds at lunar poles (1)</td>
</tr>
<tr>
<td>Determine the mineralogical, elemental, molecular, and the isotopic makeup of volatiles.</td>
<td>4b - Determine the source(s) for lunar polar volatiles</td>
<td>Determine vertical distribution and concentration of volatile compounds in lunar polar regolith (1)</td>
</tr>
<tr>
<td>Characterize the environment relevant to volatile retention</td>
<td>4c - Understand the transport, retention, alteration, and loss processes that operate on volatile materials at</td>
<td>Determine lateral distribution/concentration of volatile compounds in lunar polar regolith (1)</td>
</tr>
<tr>
<td>Investigate the geotechnical characteristics of the polar regolith within and around permanently shadowed regions (i.e., cold traps).</td>
<td>4d - Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith</td>
<td>Determine the secondary alteration mineralogy of the regolith (2)</td>
</tr>
<tr>
<td>SCEM Science Goal</td>
<td>RP Payload</td>
<td>SKG</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| 4a - Determine the compositional state (elemental, isotopic, mineralogic) and    | - Drill cuttings; GCMS analysis of surface and subsurface volatiles provides chemical and isotopic composition  
  compositional distribution (lateral and depth) of the volatile component in lunar  
  polar regions.  
  - NIR spectra provides mineralogy  
  - Neutron spectroscopy provides lateral and approximate depth distribution  
  - NIR spectra of extracted drill cuttings provides vertical distribution, as does    | D-6 Composition, Form, and Distribution of Polar Volatiles                          |
| 4b - Determine the source(s) for lunar polar volatiles.                          | - GCMS: Chemical and isotopic composition point to sources  
  - NIRVSS: imagery of physical state and NIR spectra inform emplacement mechanism.  | D-7 Temporal Variability and Movement Dynamics of Surface-Correlated OH and H2O deposits towards PSR retention. |
| 4c - Understand the transport, retention, alteration, and loss processes that    | - Drilling/sampling within PSRs: GCMS chemical and isotopic composition reveal likely sources  
  operate on volatile materials at permanently shaded lunar regions                  | D-7 Temporal Variability and Movement Dynamics of Surface-Correlated OH and H2O deposits towards PSR retention. |
| 4d - Understand the physical properties of the extremely cold (and possibly    | - Rover slip vs slope, drill penetration force and augering torque with depth, and imaged rover wheel/surface interaction provide geotechnical info  
  volatile rich) polar regolith.                                                   | D-3 Geotechnical characteristics of cold traps  
  D-4 Physiography and accessibility of cold traps  
  A-1,2 Technology for excavation of lunar resources  
  C-2 Lunar surface trafficability: In-situ measurements  
  D-2 Regolith adhesion to human systems and associated mechanical degradation     |
| 4e - Determine what the cold polar regolith reveals about the ancient solar      | Not directly addressed.                                                                                                                     | No Associated Knowledge Gap                                                           |
|  environment.                                                                   |                                                                                                                                                                                                          |                                                                                       |
Summary

RP Exploration goals cross-cut Science Goals
- Specifically, to understand volatile composition, abundance and spatial distribution, an RP-type mission is necessary

Volatile (water) are not uniformly distributed, hence, mobility and subsurface access is needed
- Distances of 10s to 100s of meters and subsurface access are required to adequately characterize volatiles (water) and address both SKGs and SCEM/Decadal Science goals associated with water lateral and vertical distributions

The RP Payload is focused and optimized to characterize polar volatiles
- The approach and techniques have been demonstrated in numerous tests under lunar-like conditions
- RP adopts the proven approach that USGS has used for decades too characterize resources

Operations at the Lunar Poles has a unique set of considerations, constraints and opportunities
- Specialized tools and data sets developed to optimize rover, instrument and CONOPS designs
- Multi-Lunar day missions can be achieved with solar power only
This overall presentation is just Volume 1 of a larger RP summary package of content.

It can be found on the RP SharePoint site along with additional volumes detailing to a greater depth important RP team development areas, looking towards PDR.

All volumes of the RP summary package can be found at:
https://sharepoint.msfc.nasa.gov/sites/fppo/FP30/AES/RP/Reviews/CloseOut%20Review/Forms/AllItems.aspx

- **Volume 1:** Project & Mission overview
- **Volume 2:** Site Analysis & Traverse Planning
- **Volume 3:** Payload detailing
- **Volume 4:** Rover/mobility detailing
- **Volume 5:** Designing for Lunar Ops
Resource Prospector Workforce Map

NASA ARC
Silicon Valley, CA
Mission & Science Mgmt., Payload Prospecting Instruments, Rover SW & Mission Ops
FTE = 159.1 | WYE = 187.7

Honeybee Robotics
Pasadena, CA
Payload Drill Development
Off-Site WYE = 15.4

NASA JSC
Houston, TX
Rover Management & Development, Payload Instrument Development, Lander Development
FTE = 119.3 | WYE = 82.6

NASA GRC
Cleveland, OH
Payload TVAC Chamber Testing, Rover Mobility & Terramechanics Testing
FTE = 4.1 | WYE = 1.2

NASA KSC
Cape Canaveral, FL
Payload Management & Operations, Payload Instrument Development, Rover Mobility Testbeds
FTE = 111.4 | WYE = 59.6

NASA HQ
Washington, DC
Agency Management

Commercial Lunar Lander Partnership (TBD)
Lunar Lander services

Payload Partners: Blue Sun [software tools] (CO), Brimrose [prospecting payload sensor] (MD), Inficon [payload instrument sensor] (NY)
Science Team Participants: APL (MD), ARC (CA), GRC (OH), GSFC (MD), JSC (TX), KSC (FL), PSI (AZ), SETI (CA), UCF (FL)

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RP is well-positioned toward a lunar lander Commercial Partnership acquisition model.

RP is a pathfinder for working with industry: RP’s WBS structure is reorganized to support commercial launch, lunar transit, and landing services.
• Aerospace Corp was performed an independent cost feasibility assessment on the RP Surface Segment (Rover + Payload)

• Aerospace used both adjusted analogies and cost models to estimate these WBS elements

• Traditional cost modeling methods were used with a series of interviews between Aerospace and the project team to accurately reflect how the team behaved under the class D construct, relative to the cost model inputs

• The project did not share its own cost estimates, prior to the ICE results being provided

“Results show that overall cost estimate is within reasonable agreement with Project’s estimate assuming heritage is retained and Class D acquisition approach is followed”

“Substantial savings can be realized with current project approach as compared to typical Class B planetary rover acquisition”

- The Aerospace Corporation

Aerospace Class D Basis Factors:
• Management Complexity
• Systems Engineering complexity
• Component Level complexity
• Development Complexity
• Requirements Volatility
• Construction Process
- Aerospace also used analogies & wrap factors to estimate the whole mission cost
  - The basis presumed an International partnership with Taiwan for the lander
  - Taiwan design/management overhead included in the Aerospace estimate

<table>
<thead>
<tr>
<th>FY17$M</th>
<th>Project Estimate</th>
<th>Aerospace ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission PM/SE/MA</td>
<td>$26M 19.7</td>
<td>$37.5</td>
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<tr>
<td>Payload</td>
<td>$63M 55.4</td>
<td>$56.4</td>
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<td>Rover</td>
<td>$70M 64.2</td>
<td>$64.6</td>
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<td>Lander*</td>
<td>$00M 59.0</td>
<td>$00M 59.0</td>
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<tr>
<td>System I&amp;T</td>
<td>$11M 12.3</td>
<td>$13.3</td>
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<tr>
<td>Science/GDS/MOS</td>
<td>$58M 43.2</td>
<td>$46.0</td>
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<tr>
<td>Launch Vehicle I&amp;T</td>
<td>$03M 1.8</td>
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<tr>
<td>Reserve</td>
<td>$69M 76.6</td>
<td>$66M -79.5</td>
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<tr>
<td><strong>Phase B-F Total</strong></td>
<td><strong>$300M 332.1</strong></td>
<td><strong>$286M 358.1</strong></td>
</tr>
</tbody>
</table>

*Italics indicates project values; treated as pass-through
$96M Taiwan lander contribution used in WBS 1.0 wrap calculations
Rover Cost versus Mission Class (D vs. B)

~$15M, RP15
~$70M, RP (Class D)
~$225M, RP (Class B)
# RP Schedule (7,780 line schedule)

*Pending Funding and Partnership Decisions*

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>RP Executive Summary Schedule</td>
<td>RP Schedule</td>
<td>Key Milestones</td>
<td></td>
<td></td>
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<tr>
<td>RP Project Phases</td>
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<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
</tr>
<tr>
<td>RP A: Concept &amp; Tech Rev</td>
<td>RP B: Final Design</td>
<td>RP C: Final Design</td>
<td>RP D: Launch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Key Milestones

- **Pending Funding and Partnership Decisions**
- **MSE Docs for PDR**
- **MSE Docs for CDR**
- **MSE Docs for SIR**
- **MSE Docs for DR**
- **SRA**
- **Build 2**
- **Build 3**
- **Build 4**
- **Build 5**
- **Build 6**
- **Sys I&T LSSP**
- **Launch IRD**
- **LV ICD**
- **LVA ETU-X Manifold Fab & I&T, Assembly & Test**
- **Launch Vehicle/Service Integration**
- **Package Surface Segment Storage/Shipping**
- **S/W Assurance Plan**
- **System Test Plan**
- **S/W Test Proc**
- **S/W Asst Plan**
- **Ship to KSC**

## WBS 2.0 - Mission System Engineering

- **WBS 2.0 - Mission System Engineering**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

## WBS 3.0 - Safety & Mission Assurance

- **WBS 3.0 - Safety & Mission Assurance**
  - **SAMA to SR**
  - **SR Phase 0/1**
  - **SR Phase 2**
  - **SR Phase 3**
  - **SMSR Review**

## WBS 4.0 - Science/Technology

- **WBS 4.0 - Science/Technology**
  - **Site Studies**
  - **Analyze/Dev. Final Measurement Plan**
  - **SR Phase 0/1**
  - **SR Phase 2**
  - **SR Phase 3**
  - **SMSR Review**

## WBS 5.0 - Payload

- **WBS 5.0 - Payload**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

## WBS 6.0 - Rover

- **WBS 6.0 - Rover**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

## WBS 7.0 - MOS

- **WBS 7.0 - MOS**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

## WBS 8.0 - Launch Vehicle/Services

- **WBS 8.0 - Launch Vehicle/Services**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

## WBS 9.0 - GDS

- **WBS 9.0 - GDS**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

## WBS 10.0 - System I&T

- **WBS 10.0 - System I&T**
  - **System Engineering**
  - **Subsystem Assembly & Test**
  - **Critical Path to Launch by Phase**

---

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Project Closeout is the CP driver to Launch

Rover’s SW Build Is the next start of the Critical Path
RP Schedule: EX: Rover TRL6 Schedule <snip>

Rovers driver to TRL6
LCROSS lesson-**affirmed**: Class D *demands* Risk Management

- Class D projects have constrained $ and calendars; RM is essential to understand where to invest resources vs accepting residual risk
- RP is a pathfinder of novel risk management approaches
  - RP risk consequence based on FSR and UFE remaining not cost & schedule overrun
    - Enables a PM to manage risk within allotment of resources; perfect for constrained projects
  - RP innovated quantifying technical risk consequence
    - No more “gut” assessments of technical consequence
    - RP pioneered a dual-weighted spreadsheet to assess consequence to the RP requirements, returning a score for the 5x5 risk scale

If the Risk Classification of RP were to be changed, this team would adapt to fit the new basis, using the same tools that exist today
### RP Risks 5x5 (Current and Lifecycle Risks)

#### RP Risk 5x5:

<table>
<thead>
<tr>
<th>Consequences</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>G</td>
<td>Y</td>
<td>R</td>
<td>R</td>
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</tr>
<tr>
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<td>Y</td>
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<td>R</td>
<td>R</td>
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<td>1</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

#### RP Risk Retirement burndown:

<table>
<thead>
<tr>
<th>Approach</th>
<th>Risk Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Comm Loss - Surface Multipath</td>
</tr>
<tr>
<td>W</td>
<td>System Outgrows Mass Allocation</td>
</tr>
<tr>
<td>W</td>
<td>Falcon 9 performance maturation</td>
</tr>
<tr>
<td>R</td>
<td>Rover Comm System Late Delivery</td>
</tr>
<tr>
<td>R</td>
<td>Comm Loss - Unforeseen Line-of-Sight Blockage</td>
</tr>
<tr>
<td>R</td>
<td>Negative Obstacle</td>
</tr>
<tr>
<td>R</td>
<td>Rover Getting Stuck in a PSR</td>
</tr>
<tr>
<td>R</td>
<td>Volatile Retention During Regolith Sample Capture and Transfer</td>
</tr>
<tr>
<td>W</td>
<td>Lander Partnership backdriving RP L2s</td>
</tr>
<tr>
<td>W</td>
<td>Sampling cross contamination</td>
</tr>
<tr>
<td>R</td>
<td>Ops Planning Hindered by Low Resolution Data</td>
</tr>
<tr>
<td>R</td>
<td>Positive Obstacle Collision</td>
</tr>
<tr>
<td>M</td>
<td>Integrated Thermal Analysis Development - Instrument Impacts</td>
</tr>
<tr>
<td>R</td>
<td>Drill Subsurface Temperature Measurement</td>
</tr>
<tr>
<td>W</td>
<td>Drill Becomes Stuck</td>
</tr>
</tbody>
</table>

---

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Engaging University Teams (X-Hab Challenge)

• Reduced Gravity Airborne Mobility Testbed Project
  – University of Vermont team
  – Simulate rover wheel/soil interaction in 1/6G
  – May fly on reduced gravity aircraft

• Using NASA Systems Engineering Processes
• Successfully completed CDR on 2/15/18
• Toured the Simulated Lunar Operations Facility (SLOPE) at NASA-GRC in December
• Visited NASA-ARC at end of March
RP Education and Public Outreach

**Numerous Media Streams**
- Media articles
  - NASA EDGE
  - NASA in Silicon Valley: Uland Wong Talks About Robots on the Moon
  - Houston Chronicle Article
- ex: #StateOfNASA Social Media Day
- Silicon Valley Comic Con (2017, 2018)
  - Panel and Booth

**Various Presentations**
- Posters: 23
- Talks/Conferences: 81
- Publications: 18

**Student Outreach**
- ex: X-Hab
- Interns: 14+
- Tours/Shadows: 7
- Classroom Events: 12
"Accelerating the Launch of Resource Prospector: The LEAG community strongly supports this mission be flown without any further delay and encourages an accelerated development to flight”
– LEAG Annual Meeting Summary Finding, 2017

“The discontinuation of the Resource Prospector Mission leaves a large hole in the path towards in situ resource utilization (ISRU) of lunar volatiles. The considered, professional assessment of the FOLNV is that a mobile, polar, volatile-prospecting mission is the essential logical next step in lunar exploration.”
- Friends of Lunar/NEO Volatiles (FOLNV), 2018

Commercial companies offer support flying RP to the moon (Blue Origin, Astrobotic)
- HoR CJS Subcommittee testimony, 2017-09
Why RP?

• RP answers critical questions for Exploration, addresses lunar Science goals, and path-finds new partnering models for the Agency

• RP is pathfinding new ways of doing business
  – RP’s novel org structure is aligned to partner with US commercial industry
  – RP PM participating in SOW generation for Lunar Cargo Services

• RP independent tech reviews confirm a solid forward plan
  – Reviewers from both inside and outside the Agency

• RP LCCE and Aerospace Corp ICE in strong alignment
  – “Substantial savings can be realized with current project approach as compared to typical Class B planetary acquisition” – Aerospace Corp

• RP received NASA’s Systems Engineering Excellence Award and Innovation Award for novel approaches
For Science.
For Commerce.
For Policy.

The right Mission.
The right Team.
The right Time.

资源勘探者 Zīyuán kāntàn zhě
("Resource Prospector" in Chinese)
Backup
<table>
<thead>
<tr>
<th>Hitch a ride…</th>
<th>Self-Check…</th>
<th>Find &amp; Excavate Volatiles…</th>
<th>Collect &amp; Process the volatiles…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>Quick Checkout</td>
<td>Use the Neutron Spec &amp; Near-IR Spec to look for Hydrogen-rich materials</td>
<td></td>
</tr>
<tr>
<td>Lunar Transfer</td>
<td>Quick Checkout</td>
<td>Study different terrain types</td>
<td>Use the Drill Subsystem to capture samples from up to 1[m] depth</td>
</tr>
<tr>
<td>Lunar Orbit (?)</td>
<td>Roll-off Lander</td>
<td>Expose regolith</td>
<td>Heat regolith (150-450 degC) in the WAVE OVEN Subsystem</td>
</tr>
<tr>
<td>Descent &amp; Landing</td>
<td>Begin Surface Ops</td>
<td>Use the Drill Subsystem to expose material from 1[m] depth to examine with Near-IR Spec</td>
<td></td>
</tr>
</tbody>
</table>

US Commercial industry Role

RP in Storyboard form

Quick Checkout

Map surface

Study different terrain types

Exposed regolith

Capture regolith

Heat regolith

Identify Volatiles

Show me the water!

Use the Drill Subsystem to find & excavate volatiles...

Heat samples (150-450 degC) in the WAVE OVEN Subsystem.

Determine type and quantity of volatiles in the WAVE LAVA Subsystem. (H2, He, CO, CO2, CH4, H2O, N2, NH3, H2S, SO2)

Image and quantify the water created using the WAVE LAVA Subsystem.

RP in Storyboard form

Quick Checkout

Map surface

Study different terrain types

Exposed regolith

Capture regolith

Heat regolith

Identify Volatiles

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