Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) for Robotic Lunar Polar Lander Mission

Gerald B. Sanders[1], Landon Moore[1], David S. McKay[1], Tom M. Simon[1], Dale E. Lueck[2], Clyde F. Parrish[2], Kenneth R. Johnson[3], Greg Mungas[3], Mike Pelletier[3], Kurt Sacksteder[4], Michael Duke[5], Jeffrey Taylor[6], Larry Taylor[7], Dale Boucher[8]

[1]NASA/Johnson Space Center, 2101 NASA Rd 1, Houston, TX 77058
[2]NASA/Kennedy Space Center, FL 32899
[3]Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109
[4]NASA/Glenn Research Center, 21000 Brookpark Rd. Cleveland, OH 44135
[5]Colorado School of Mines, 1310 Maple St., Golden, CO 80401
[6]University of Hawaii, 1680 East-West Rd., Honolulu, HI 96822
[7]University of Tennessee, 306 EPS Bldg., Knoxville, TN 37996
[8]NORCAT Inc., 1400 Barrydowne Rd., Sudbury, ON Canada P3A 3V8
(281) 483-9066, gerald.b.sanders@nasa.gov

Abstract. Ever since the Clementine and Lunar Prospector mission instrument data indicated the possibility of significant concentrations of hydrogen at the lunar poles, speculation on the form and concentration of the hydrogen has been debated. Should hydrogen or water exist in usable and easily accessible concentrations, this resource could have profound implications on the design and affordability of initial and long-term human Lunar exploration hardware and systems, lunar surface operations and mobility, Earth-Moon transportation, and transportation to Mars and beyond. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce mission cost by reducing launch mass, providing affordable pre-positioning of consumables, and enabling reusability; reduce risk by providing backup life support consumables and reduced dependence on Earth; and enable extended surface operations by providing an energy rich environment and affordable access to multiple surface targets. Even if water is present at the poles, exploration at other locations of interest on the Moon will require different methods of obtaining mission consumables, such as oxygen, and other resources of interest, such as metals and silicon. President Bush's announcement in January 2004 for the United States to return to the Moon and to further explore Mars and beyond '…including use of lunar and other space resources to support sustained human exploration…' has placed new emphasis on fundamental science questions, such as "What resources are available on the Moon, where are they, and in what form?" as well as critical engineering questions, such as "How will we mine these resources, what chemical extraction processes are the most practical and efficient, and what are the engineering challenges to be faced in this environment?" The environment in the permanently shadowed regions at the poles is especially challenging due to the extremely low temperature (<80 K) and the unknown physical properties and content of trapped gases in the regolith and ice (if present). The goal of the Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE) project is to develop and integrate a modular processing package that can answer these science and engineering questions. The RESOLVE project is being performed by a small team consisting of lunar resource, flight hardware, terrestrial mining, and ISRU processing experts from NASA, JPL, academia, and industry. The project officially started at the end of January, 2005, and this paper will outline the project's development objectives and approach, and describe the instruments, processes, and systems that are being evaluated in the 1st year, leading to development and testing of a prototype under simulated lunar polar environmental conditions by the 4th year.

INTRODUCTION AND BACKGROUND INFORMATION

Many studies have shown that the ability to process and refine materials that have been extracted and separated from in-situ resources into useful products, known as In-Situ Resource Utilization (ISRU), can have a substantial impact on individual missions and mission architecture concepts [1, 2, 3, 4]. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce mission cost by reducing launch mass and enabling reusability; reduce risk by providing backup life support consumables and reduced dependence on Earth; and enable extended surface operations by providing an energy rich environment and affordable access to multiple surface targets. Consumables of interest include oxygen, hydrogen, water, and hydrocarbon fuels.

Although oxygen is abundantly available in the minerals of the lunar regolith, no concentrated source of hydrogen was known with certainty to exist prior to the Clementine and Lunar Prospector missions. The Clementine bi-static radar and Lunar Prospector neutron spectrometer instrument data have been interpreted as indicating significant concentrations of hydrogen in the permanently shadowed craters on the Moon[5,6]. The actual form and concentration of the hydrogen is uncertain since the neutron spectrometer only detects the presence of hydrogen and the resolution of the data is 10's of km per pixel.

Lunar polar regions (longitude >75°) are illuminated at low Sun angles. Because of abundant craters, some areas are permanently shadowed. Dark areas inside large (> 40 km in diameter) craters can have temperatures ranging from 40 to 100 K, depending on how much reflected sunlight they receive from crater walls and other topographic features[7] . These temperatures are cold enough to preserve condensed ice for billions of years if covered by a thin layer of regolith[7, 8]. Although shielded from the Sun, polar shadowed areas are still bombarded by solar wind when the Moon passes through Earth's magnetotail. The dark regions are also irradiated by Lyman-α UV radiation and galactic cosmic rays; the former might erode ice deposits, while the latter might add energy to the regolith to drive chemical reactions involving hydrogen, water, and other volatile substances[9].

Based on analysis of Clementine and Lunar Prospector data, it is estimated that craters in the south polar regions contain 1700 ± 900 ppm of hydrogen. If this is in the form of water ice, it translates to 1.5 ± 0.8 wt%. and local areas could contain up to 10 wt% water, clearly a significant resource[10]. If the primary source of this water were comet impacts, then water would still be the most abundant volatile (comprising 80% of the deposit), but would be accompanied by other frozen compounds (CO, CH_3OH, CO_2, NH_3 and CH_4, plus traces of other compounds)[11]. Models of cometary impact and material migration at high latitudes suggest that a deposited layer of at least 10 cm thick is needed to be noticeable as discrete layer in the regolith after a billion years[12, 13].

The source of hydrogen detected could have profound implications on the design and affordability of long-term lunar surface operations, Earth-lunar transportation, and even transportation to Mars and beyond. The ability to produce oxygen and fuel from lunar resources would obviate the need to transport propellant to the Moon, and reduce the scale of Earth launch requirements for lunar missions and sustained surface exploration. The presence of high concentrations of water and/or hydrogen would allow less complex and less energetic processes compared to the systems needed to produce oxygen and fuel from oxide and silicate minerals or solar wind deposited molecules in the lunar regolith.

RESOLVE OVERVIEW AND OBJECTIVES

Before lunar resources can be utilized in robotic and human exploration missions to reduce mission mass, cost, or risk, it is important to characterize the form and concentration of the resources in the permanently shadowed craters, understand the environment the resource is found in, and adequately validate that the processes required to extract and process the resource will operate in the environment for the desired mission duration. Experience with the Deep Space 1 mission shows that successfully demonstrating new technologies and capabilities (like ion propulsion) can fundamentally change how future missions are designed & implemented. To meet this need, the Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) project is developing and integrating an experiment package that can perform the following objectives; (1) obtain "Ground Truth" data for resources at lunar pole; (2) obtain bulk and fine-grained regolith characteristic and environment data; (3) extract and collect volatiles from regolith; (4) produce oxygen from regolith; and (5) perform a hydrogen/water resource processing demonstration after it has been evolved and collected (must deal with uncertainty in form of hydrogen found). The integrated experiment package is being designed and built to eventually operate under simulated lunar permanently shadowed crater environmental conditions (TRL 6). The goals of the RESOLVE project are to enable the understanding of the polar resources and environment on the Moon, and to obtain the data and experience necessary to design follow on hardware to extract and process these resources into useful mission products. To meet these objectives and goals, five modules are being developed to integrate into a single polar resource characterization and ISRU demonstration unit:

1. **Excavation and Bulk Regolith Characterization (EBRC)**: Provides the capability of extracting samples of regolith from the lunar subsurface (to 1 meter depth) and deliver a suitably conditioned sample to the

remaining modules. This module will also support determination of bulk regolith characteristics for future excavation system design.

2. **Environment and Regolith Physical Characterization (ERPC)**: Determines the fine-grain characteristics of regolith samples (such as mineral and chemical composition and in-situ size distribution) and the ambient temperature in the permanently shadowed crater.
3. **Regolith Volatile Characterization (RVC)**: Provide capability of evolving and measuring volatiles from regolith samples to determine the form and concentration of hydrogen bearing molecules in shadowed regions near the lunar poles.
4. **Regolith Oxygen Extraction (ROE)**: Demonstrate the ability to chemically extract oxygen from the regolith samples.
5. **Lunar Water Resource Demonstration (LWRD)**: Demonstrate the ability to capture and quantify water and hydrogen produced/evolved by the ROE and/or RVC from the regolith samples. In addition the LWRD shall split the water that is captured into hydrogen and oxygen using electrolysis.

As stated above, the two primary objectives for RESOLVE are to characterize polar resources and the environment and to demonstrate ISRU processes to the degree needed to minimize the risk of follow on resource and ISRU processing missions to the Moon. Table 1 below lists the RESOLVE objectives as a function of these two primary objectives as well as additional experiment goals if payload and mission design allow.

TABLE 1. RESOLVE Objectives

Resource Characterization	1	Determine form and concentration of hydrogen in permanently shadowed regions	*Science-Resource Focused*
	2	Determine other volatiles available	
	3	Determine grain size distribution and morphology of regolith	
	4	Determine quantity of which volatile(s) are evolved by excavation and crushing/agitation	
	5	Determine chemical/mineralogical properties	
In-Situ Resource Utilization	6	Determine bulk excavation related physical properties of the regolith	*Engineering-Processing Focused*
	7	Demonstrate capture and separation of water	
	8	Demonstrate oxygen extraction	
	9	Engage & excite public/Education Outreach	
Additional experiment goals if payload & mission design allow	G1	Determine difference between sunlit and shadowed regions	Rover Required
	G2	Determine spacial distribution of resources	Rover Required
	G3	Demonstrate scalable extraction/processing techniques	
	G4	Demonstrate scalable oxygen production technique	

Because the regolith and water characterization and extraction hardware under development may also be used to answer similar water resource questions on Mars, RESOLVE is being designed to be the first step in regolith ISRU development for the Moon and Mars. Experience for the design, development, test, and eventual flight of RESOLVE will provide critical data and experience for subsequent ISRU missions.

RESOLVE PROJECT OVERVIEW

The RESOLVE project was initiated through the Exploration Systems Mission Directorate (ESMD) Intramural Call for Proposals (ICP) under the Technology Maturation Program. This project, started Feb. 1, 2005 is divided into two phases; Phase I (1st year) and Phase II (2nd through 4th years). The purpose of Phase I is to evaluate experiment options, validate critical experiment features, and provide a logical development plan with credible cost and development risk. Phase I, tasks include: (a) Identifying critical requirements & measurements; (b) Performing trades to define preliminary designs for the two experiment options; (c) Performing literature review of processes and sensor options; and (d) Performing laboratory tests to demonstrate concept feasibility, anchor design specifications & requirements, and reduce risk for the remaining development activity In Phase II, experiment modules will be designed, built, and tested, first individually, and then as an integrated package. To minimize cost and time, existing designs and hardware will be utilized to the maximum extent possible. Hardware and sensors may be shared between experiment modules (ex. gas analysis module, regolith delivery hardware, and thermal chambers). A centralized controller, data collection, storage, and transmission, and power conditioning unit will be designed to operate the integrated RESOLVE experiment, however each major RESOLVE element will be responsible for designing and developing the control electronics required to operate the element. Phase II hardware will be developed in two steps; an Engineering Breadboard Unit (EBU), and Final Prototype Unit (FPU). The purpose of EBU is to evaluate early integration and experiment operation issues. The EBU will not be forced to meet flight-like mass, volume, and power requirements, and therefore will most likely not be operated under simulated lunar environmental conditions. Individual EBU elements may be operated under simulated lunar environmental conditions if early validation of concepts or hardware is required. The FPU will be designed to be within 15% of flight mass, power, and volume and will be operated for at least one week of simulated lunar polar environmental testing. Some items may be excluded from the FPU mass, volume, power, and lunar operation requirement if the hardware already exists but is expensive (ex. mass spectrometer), or significant cost and schedule is associated with the design and fabrication of flight-like hardware (i.e. control electronics, software, and the warm electronics box).

RESOLVE TEAM

The RESOLVE project is being performed by a small team consisting of lunar resource, flight hardware, terrestrial mining, and ISRU processing experts from NASA, JPL, academia, and industry. Each team member brings unique and critical expertise to enable the science and engineering goals and objectives for the integrated RESOLVE experiment. Team member design, hardware, and instrument experience from Regolith Evolved Gas Analyzer (REGA) and Camera, Hand Lens and Microscopic Probe (CHAMP) development and Mars In-situ propellant production Precursor (MIP) & Microscopy, Electrochemistry, & Conductive Analyzer (MECA) flight experiments will be utilized.

JSC will lead the RESOLVE project, and ensure science and engineering objectives are met through the Principal Investigator, Project Manager, Chief Scientist (CSci), and Chief Engineer (CEng) positions. Through the CSci and CEng, JSC will lead both the Science Advisory Team (SAT) and System Engineering and Experiment Integration Team (SEEIT). JSC will also lead the design and development of the ROE module. KSC will lead the design and development of three RESOLVE modules: EBRC, RVC, and the LWRD. JPL will lead the design and development of the ERPC module. Because of JPL's unique and significant experience with the design, development, and operation of planetary surface rovers, experiments (MIP & MECA), and regolith science and excavation instruments, JPL will provide support to the SAT, SEEIT, and the EBRC & LWRD modules. Other NASA team members include GRC and MSFC. GRC will support design and development of the EBRC & RVC modules. MSFC will provide overall support to the RESOLVE project through involvement in the SEEIT as well as lunar regolith simulant specifications and development.

Academia team members include the Colorado School of Mines (CSM), University of Hawaii, University of Tennessee, and Lunar Geotechnical Institute. These universities have unique and extensive experience in lunar and planetary geology, and through the SAT will provide critical expertise to defining and ensuring RESOLVE science objectives are met. CSM also has significant experience and capabilities in ISRU processing, terrestrial and space mining techniques, hardware design & development, and economics that will be used to support the EBRC, RVC, ROE, and LWRD module development.

Industry team members include Orbital Technologies Inc. (ORBITEC), Boeing, and the Northern Centre for Advanced Technology (NORCAT). ORBITEC and Boeing will perform design and tests of their approach to the ROE module in Phase I, with downselect to full development in Phase II. CSM and JSC are also developing ROE module concepts in Phase I. NORCAT will design, build, and test hardware for the EBRC module.

MISSION & OPERATING REQUIREMENTS

Based on Clementine and Lunar Prospector mission data, scientists and engineers are trying to determine possible sites of interest for future science and human Lunar exploration. Sites of interest include locales at the Lunar poles that are (a) close to areas of high hydrogen concentration, (b) are close to areas of near-permanent sunlight (>70%), and (c) have terrain which is conducive to landing near and surface mobility into and around permanently shadowed craters that hold the resources of interest. Given that the water/hydrogen resolution of Clementine and Lunar Prospector mission data is at 10's of km per pixel, and terrain photography and lighting map resolution are not adequate to finalize site selection, NASA has initiated the Lunar Reconnaissance Orbiter (LRO) mission to fly to the Moon in 2008. LRO will carry six primary payloads[14] and one secondary payload to conduct investigations that will be specifically targeted to prepare for and support future human exploration of the Moon. The Advanced-Moon micro-Imager Experiment (AMIE) on the European Space Agency (ESA) Small Missions for Advanced Research and Technology (SMART-1) mission is being used to provide high resolution images as well as identify shadowed and permanently lit sites on the Moon over a complete year timeframe[15]. The SMART-1 and LRO missions currently underway or planned will provide critical data on where hydrogen/water concentrations will best be found and what locations are accessible. However, neither of these missions (or other planned Lunar orbiters by India and China) will provide the "ground truth" needed to conclusively determine the source of hydrogen measured by Lunar Prospector.

Because this data is critical to determining long-term human mission plans for the Moon and Mars, the goal of early robotic Lunar lander mission(s) will likely be to determine what is in the permanently shadowed craters of the lunar poles, what form and concentration is it found in, and how difficult is it to extract and process. Actual payload requirements and specifications for early Lunar lander missions are not available at this time, nor is it known whether the mission will include a rover, a short life lander, or multiple penetrators. However, to design the experiment modules for RESOLVE to best meet the objectives of determining the source, concentration, form, and extraction difficulty of hydrogen/ice in the permanently shadowed craters, several mission and operating requirements had to be assumed.

Mass and Power: Because it is not known at this time whether there will be a stationary lander or rover, RESOLVE will be designed to be as small and low power as possible. Therefore, the target mass and power for RESOLVE is 30 kg mass and 100 watts of power maximum. These values are based on comparison to Mars Exploration Rover (MER) and Mars Science Laboratory (MSL) rover payloads and capabilities.

Payload Accommodations: RESOLVE is designed to be a payload on a lander or a rover. It is assumed that the host will provide power, communications, and mobility (if applicable). RESOLVE will be designed to control its own operations and store data until the host transmits. For this development program, it was assumed that a neutron spectrometer for resource reconnaissance would be provided by the rover. Near flight ready neutron spectrometers can be obtained from Los Alamos National Laboratory.

Sample Collection & Preparation: RESOLVE will incorporate a drill to obtain samples for resource characterization and ISRU demonstrations. The drill will allow a 1 meter core to be extracted and includes a core capture mechanism to minimize volatile losses. RESOLVE is currently being designed to perform a minimum of 3 drilling operations and a nominal 10 drilling operations under 40 K temperature and vacuum conditions. Cores will be transferred to the processor in 4 segments, and each segment will crushed down to 1 mm before transferring to the RVC or ROE. This will allow for measurement of resource concentration by depth. Volatiles that are released during segment transfer and crushing will be measured (species and amount). Drill length and number of individual segments can be changed to meet specific mission requirement needs at a later date.

Bulk and Fine Regolith Characterization: RESOLVE will measure critical excavation and bulk regolith characteristics during sample collection drilling. Separately, RESOLVE will measure fine grain regolith properties including shape, size distribution, and mineral/chemical characteristics.

Water/Volatile Processing: RESOLVE will process each core segment (4 per core drill operation) individually. RESOLVE will include a method to capture and separate both water and hydrogen released during crushing and RVC operation. A nominal 0.25 to 2 ml of water total (if present from 3 core sample operations) will be collected, separated, condensed, and visually verified. Water will be split after capture through electrolysis. Volatile species will be measured (under 100 AMU).

Oxygen Production From Regolith: RESOLVE will incorporate a method to extract oxygen from regolith. A minimum of 2 operations will be performed to validate sealing and feedstock/spent regolith transfer. The ROE will produce a minimum of 5 grams of oxygen per operation with 80 watts of power maximum during operation.

Rover Operations: If a rover is available, the RESOLVE package will perform the following evaluations at a minimum of 3 locations and 10 locations nominal: core sample collection, bulk & fine regolith characterization, hydrogen/water and volatile release processing. A sequence of operations will need to be performed to meet mission objectives. This sequence will include first locating an area of 'high' hydrogen concentration, collecting a sample of material at this location down to a depth of 1 meter, delivering the sample in discrete, segregated samples so that depth distribution of resources can be measured, and conditioning the samples for delivery to the ERPC, RVC, or ROE modules. Once this sequence of operations is completed, the rover/RESOLVE unit will traverse until it identifies another 'high' hydrogen concentration, and the complete sequence begins again.

Autonomy: RESOLVE is being designed to operate as autonomously as possible. Because direct line-of-sight communication with Earth will most likely not be possible, communication between Earth and RESOLVE may only be possible via relay through the Lunar Reconnaissance Orbiter. Based on mission length and over-pass limitations, only periodic direct commanding may be possible. Therefore, RESOLVE will be designed to the maximum extent possible to rely primarily on RESOLVE-to-Earth status and data transfer as the primary communications path and Earth-to-RESOLVE command communication limited to periodic commanding, contingences, and failure recovery.

RESOLVE ACTIVITIES AND ACCOMPLISHMENTS TO DATE

Even though RESOLVE only started on Feb. 1, 2005, a significant amount of work has been performed in all areas. The following is a description of RESOLVE activities and modules and the accomplishments that have been achieved to date.

Science Advisory Team (SAT)

The main purpose of RESOLVE is to determine and characterize the unknown resources and environmental conditions to be found in the permanently shadowed craters of the Moon's poles. However, before engineers can design, build, and test hardware to perform this task, an 'educated guess' must be made for these unknowns to base the designs on. It is the purpose of the Science Advisory Team (SAT) to define these educated guesses through data review and laboratory testing that will provide the basis for subsequent RESOLVE hardware development. To date, the SAT has addressed or is currently addressing the following issues:

- Ice sublimation rate at extremely low temperatures and pressures
- Probability of hitting a rock given a known drill bit diameter
- Permanently shadowed lunar regolith property estimation (through thermal vacuum testing of very low temperature mixtures of water and stimulant)
- Trace element identification for sensor and processing hardware poisoning concerns
- Polar regolith subsurface temperature profile
- Likelihood of volatile loss due to regolith heating from drilling
- Lunar polar simulant definition and production to allow testing of each experiment module

In particular, significant work has been performed in determining the regolith properties of permanently shadowed lunar regolith and development of a lunar polar simulant. Initial testing by JSC on bulk JSC-1/ice mixture (at liquid nitrogen temperature) characterization testing has been performed to provide a range of expected hardness/ compactness. This, combined with ORBITEC JSC-1/ice mixture characterization testing has provided early design specifications for RESOLVE. The University of Hawaii is currently developing more precise characterization testing procedures. In the area of lunar polar simulant development, simulant material for polar regolith physical and mineralogical requirements has been located by NORCAT and the University of New Brunswick and processing (crushing and melting) to obtain the desired mineral, rock, and breccia fragments, glasses, and agglutinates has begun. This new simulant can be mixed with JSC-1 to tailor the physical and mineralogical characteristics of the lunar polar stimulant.

Excavation & Bulk Regolith Characterization (EBRC) Module

The first step in the utilization of lunar resources for robotic and human exploration is to excavate lunar regolith. Significant uncertainty exists as to the physical characteristics of the regolith found in the permanently shadowed craters in the polar regions of the Moon. Also, the high vacuum, high thermal gradient, extreme temperature conditions, and reduced gravity environment of the Moon pose challenges never before encountered in the mining industry. Therefore, before large scale resource extraction and processing operations can occur, the interaction of the excavation device with the regolith, the impacts of the lunar environment on excavation designs and performance, and the physical and bulk characteristics of the regolith must be determined. Bulk regolith characteristics of interest include internal angle of friction, bearing strength, compaction, layering, and bulk density. Besides needing to understand these characteristics at different regolith depths, determining these characteristics at multiple locations is highly desired.

For terrestrial applications, excavation systems are highly specialized for particular materials, resources of interest, or scale of operation. No one system can perform all duties efficiently in all materials; therefore, several excavation systems are often utilized in different phases of an operation. Based on terrestrial mining experience and knowledge of the lunar environment and potential resource physical and material composition, the RESOLVE team will design, build, and test the Excavation & Bulk Regolith Characterization (EBRC) module which will include an excavation device with the ability to remove regolith down to 1 meter depth and deliver segmented and processed regolith to regolith characterization, volatile extraction, and oxygen production demonstration modules. This team is lead by the Kennedy Space Center and includes the Colorado School of Mines and the Northern Centre for Advanced Technology (NORCAT). The excavation device will use sensors and motor torque/power to measure the force required to excavate the material as a function of depth. Since excessive agitation and handling during excavation could cause volatile resources to separate before the regolith can be processed, a core capture mechanism will be included in the excavation device. Because lunar regolith is highly abrasive, consideration will be given to both minimize mechanical wear as well as measure and quantify the effects or lunar regolith abrasion on the excavation device developed for the RESOLVE experiment.

To date, a custom drill bit and auger has been designed to handle expected lunar permanently shadowed crater regolith and both are in fabrication. The core capture device to minimize volatile losses has been designed and a prototype is complete. A roll crusher to both prepare the regolith for delivery to the RVC and ROE modules and to evaluate the release of volatiles due to agitation has been designed and fabrication has started. It should be noted that a significant amount of knowledge, experience, and in some cases hardware has been incorporated into RESOLVE from past and current Mars drill related work at NORCAT being funded by the Canadian Space Agency (CSA). NASA and CSA have coordinated these programs and further collaboration in Phase II and flight is being considered.

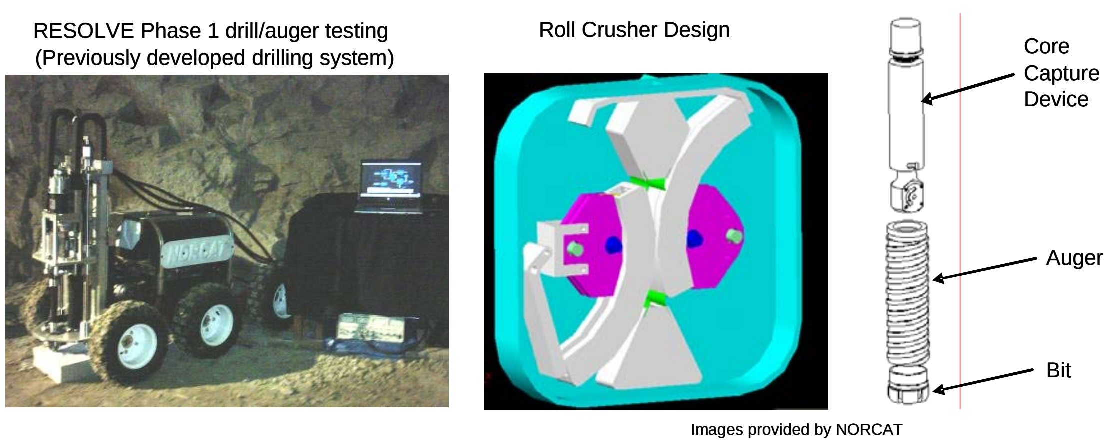


FIGURE 1. EBRC breadboard hardware

Environment & Regolith Physical Characterization (ERPC) Module

The effects of micrometeorite bombardment dominate the physical properties of the lunar regolith, and there is no expectation that these processes are any different in the permanently shadowed areas of the lunar poles. Therefore, the regolith in the permanently shadowed craters is likely to be fine-grained, contain a high percentage of glassy agglutinitic particles, and have complex, discontinuous layering [16]. If ice has been deposited within these areas, the physical properties may have been altered, with implications for extraction processes. From Apollo astronauts, experiments, and samples returned to Earth, we know that the regolith is highly abrasive. Mean grain size of surface regolith ranges from ~40 microns for mature highland soil to a few hundred microns for immature mare soil. In most regions, the regolith is very compact below 10 to 40 cm beneath the surface because of repeated micrometeorite bombardment. The fine grain sizes and fragmental nature of the regolith leads to high porosity, 35-45% at 20 cm depth, and very low thermal diffusivity, $10^{-8} m^2/s$ at 30 cm depth [17].

Going to the permanently shadowed craters of the Moon may be highly advantageous for resource extraction and utilization, but it will entail overcoming design and operational challenges that have not been encountered in any terrestrial application or space flight mission. Temperatures at the sunlit rim of these polar region craters can be as high as 270 K but may drop down to 40 K in the permanent shadows. Eclipse cooling curves suggest that the uppermost millimeter of the surface is extremely porous and could have sustained thermal gradients as high as 100 K/mm, but would become much less severe with depth, reaching about 1 K/m at a depth of about 1 m[18]. The possibility that ice deposits may bond regolith grains together forming a permafrost-like layer or that layers of ice covered by fragmental material may exist must be considered in the design.

Because fine-grained regolith properties in the permanently shadowed crater are unknown, and thermal extremes will stress hardware and complicate mechanical operations, regolith characteristics and the operating environment need to be understood to enable future resource utilization applications. Information of interest includes grain size, shape, mineral and chemical composition, and possibly abrasion/wear characteristics. A RESOLVE subteam, led by the Jet Propulsion Laboratory, will utilize concepts and expertise developed for the MIP[19] and MECA[20,21] experiments as well as the Camera, Hand Lens and Microscopic Probe (CHAMP), Mars Microbeam Raman Spectrometer (MMRS), and Soil Probe for Netlander to design and build the Environment & Regolith Physical Characterization (ERPC) module.

The goals for the ERPC are to: (1) measure the lunar regolith temperature to better than 1 K at the surface and to a depth of 10 cm, (2) characterize lunar regolith particle size, shape, and color, and image frost/ice (if present) by optical microscopy, (3) characterize the chemical composition of lunar surface regolith (components detectable to ~1 wt%), and (4) determine the form of hydrogen in hydrogen-containing materials. The CHAMP design will allow in-focus lunar images to be acquired from any working distance – the closer the target, the higher the resultant image resolution. This capability will be used both for far-field imaging of the lunar terrain as well as hand-lens and microscopic imaging of the lunar surface and regolith samples. For the ERPC module, the CHAMP design can provide the ability to resolve >90% of the total soil particle distribution in microscopy mode, which equates to a ~3 micron/pixel resolution (this requirement is based on Apollo soil sample particle distributions neglecting <10% of smallest fines), and it can provide imaging resolutions continuously from hand lens mode (~30micron/pixel) to microscopy mode (3 micron/pixel as defined above). It's field of view (FOV) at microscopy can provide sufficient overlapping image context (equates to >1.5mm FOV at microscopy) to accommodate arm placement errors (<1mm typical) if an arm is used. At microscopy the primary variable focus mechanism is used in a "fine" resolution mode to permit microscopic imaging of unimproved surfaces. Given the lack of color on the lunar surface and the very stable nature of a lunar surface mission, monochromatic far-field imaging may be performed in unlighted areas with long integration times in starlight to provide context imaging for the overall mission. Color imaging and fluorescence at hand-lens to microscopic spatial scales will be accommodated by LED illumination with red, green, blue, white, and UV light. Illumination intensity shall be sufficient to provide <1 second exposures at microscopy for typical lunar sample materials (surface albedo's based on Apollo samples).

At CHAMP peak magnification, raman point spectroscopy will be provided by an MMRS laser probe and spectrometer design integrated with the CHAMP instrument. This scanning raman laser probe nested within CHAMP's microscopic FOV will be used to indicate the forms of hydrogen present and to identify mineral content to yield measurements of regolith compositions to within 1 wt% per compound. The laser probe scanning system will accommodate two modes of operation: 1) autonomous preprogrammed scanning sequences for point-counting statistics, or 2) raman interrogation of observed image features based on man-in-the-loop feedback. Figure 2 illustrates a high level overview of the RESOLVE ERPC CHAMP/MMRS instrument.

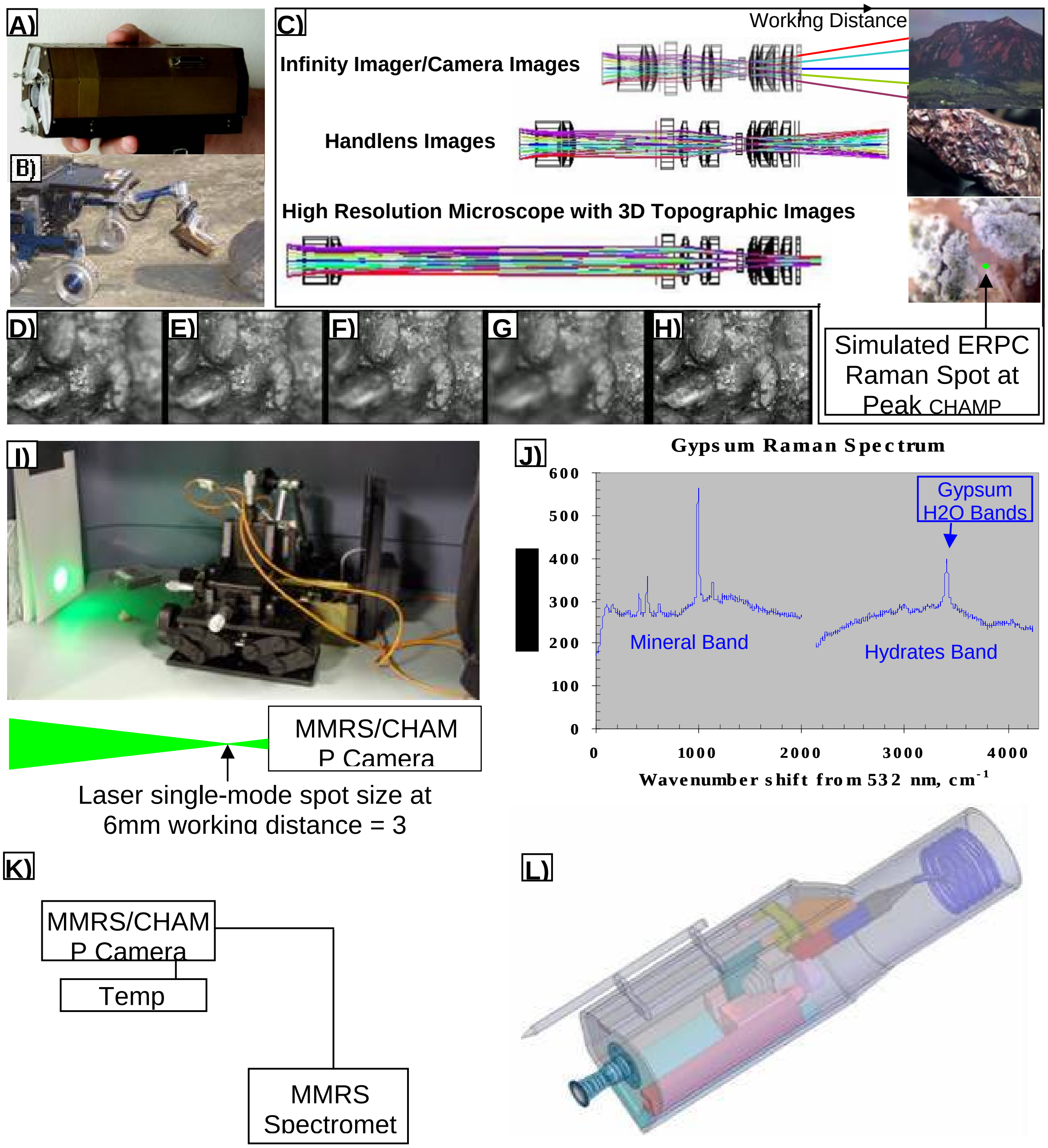


FIGURE 2. RESOLVE ERPC CHAMP/MMRS Lunar Prospecting Instrument. A) MIDP CHAMP Instrument on B) NASA Ames K9 rover during autonomous approach and arm placement exercises for field microscopy. C) CHAMP continuously variable working distance/magnification. D-H) Field microscopy of "rough" surfaces by focal plane merging images (D-G) into composite in-focus microscopic image, (H). I) First integration of brassboard MMRS and MIDP CHAMP into a Raman field microscope. J) Raman point spectra of Gypsum acquired through the CHAMP optical system showing distinct gypsum mineral and water bands. K) ERPC System Block Diagram. L) CHAMP/MMRS Camera PDR level design.

Regolith Volatile Characterization (RVC) Module

It is currently not known what form of hydrogen was measured by the Lunar Prospector neutron spectrometer instrument, nor is the exact concentration or point to point variation of concentration of this hydrogen known. Models depict the observed enrichments in hydrogen as being due to solar wind hydrogen, water ice formed after soil grains have been bombarded with solar wind hydrogen, and more complex ices released by impacting comets. These deposits could form thin films around regolith grains, partially to completely fill pore spaces, or form layers of ice (in the case of comet impacts).

Tests performed with Apollo lunar samples showed that the solar wind deposits 50-100 parts per million (ppm) of hydrogen, 3-50 ppm of normal helium, 10^{-3} ppm for the helium-3 isotope, and 100-150 ppm of carbon, and that these resources can be obtained by heating the regolith up to 900 C [22]. From these tests, it was also determined that 80% of volatiles were contained in particles smaller than 60 microns. If the primary source of the hydrogen detected is water from comet impacts, then water would still be the most abundant volatile (comprising 80% of the deposit), but could be accompanied by other frozen compounds (CO, CH_3OH, CO_2, NH_3, CH_4, and traces of other compounds). These other compounds can be either useful resources or contaminants that must be removed before resource processing can be initiated. In either case, before large-scale resource processing is possible for future human missions it is essential to understand and characterize the chemical form, content, and distribution the hydrogen and carbon-bearing molecules at different regolith depths, as well as at multiple locations if possible. The EBRC module will introduce the core samples through a roll crusher attached to the RVC module, and the RVC gas analyzer to measure any released volatile gases.

The RESOLVE Regolith Volatile Characterization (RVC) module will characterize the volatiles present by heating regolith (provided by the EBRC) in a chamber that can be sealed. Design concepts and expertise from the Regolith Evolved Gas Analyzer (REGA)[23], chemical processing and analysis at the Kennedy Space Center (KSC), and reduced-gravity effects on particle fluidization and heating from the Glenn Research Center (GRC) will be utilized to develop the RVC. The RVC oven design has two lines of development. First is a resistance heated fluidized bed design that uses a unique method of fluidization. Instead of a traditional gas stream fluidized bed, this system uses a vibrationally fluidized bed. There are several reasons for this choice. The lunar regolith has very poor thermal conductivity, which would lead to large temperature gradients in a static bed. While a very small thermal chamber (< 1 gm) size would be capable of heating such a sample, we have chosen to design a system that could be scaled to a production system for future ISRU applications. A gas-fluidized bed has a significant weight penalty in that a substantial gas flow is required to fluidize the bed. This would require a gas supply that would consume limited mass allowances. In addition, the gas fluidization flow would carry very small particles downstream where they might interfere with valves, the RVC analysis module, or the LWRD capture beds. Initial experimentation has shown that proper tuning of the frequency and energy level of vibration to the oven can produce very good fluidization and mixing for a variety of particle sizes. These initial experiments will build our understanding of the fundamental properties of vibrational fluidization and to build a model of this phenomenon that can extend this knowledge to predict bed behavior in the low gravity environment on the Moon, along with particle mixing and aerosol transport of small particles (<10 microns) with the presence of evolved gases. Future experiments are planned for 1/6 g flights aboard the NASA C-9 aircraft to confirm, extend, or modify the modeling.

Besides resistive heating, a second approach to the RVC oven design is to utilize microwaves to penetrate the regolith and produce more even heating with or without the fluidized bed. Experiments on this technology are being carried out by the University of Tennessee and require a lunar simulant that will mimic the behavior of lunar regolith in microwave absorption, which the University of Tennessee is also developing. The key change to existing simulants is the addition of nano-phase iron particles which are believed to strongly interact with microwaves, unlike current lunar simulants. At this time, the RVC oven conceptual design incorporates both the vibrational fluidization and microwave heating capabilities being examined to mitigate the poor thermal conductivity of lunar regolith. Microwave heating may have weight and power disadvantages for a small scale ISRU system, yet be highly applicable to larger systems where vibrational fluidization may be difficult. These trades will be actively examined in Phase II of the project.

The RVC will analyze the composition and mass of the volatiles generated as a function of temperature and time using a measurement system that could include a gas chromatograph (GC), mass spectrometer (MS), and/or tunable diode lasers. The evolved gases will be of uncertain composition, temperatures and pressures, ranging from high concentrations of water released at elevated temperatures to mostly hydrogen and helium released at low temperatures. The RVC analytical module must be able to accurately analyze these volatile gases and avoid potential problems with matrix effects or the appearance of unknown gases. Since hydrogen is potentially our main resource, we can eliminate IR and NIR techniques that do not respond to hydrogen. Our combined experience and that of MS experts at KSC indicates that matrix effects and water analysis by MS are both serious problems. While traditional GC analysis can excel at this type of analysis, the weight and carrier gas penalties were considered prohibitive. A recently developed MEMS based GC analyzer, with low power and mass, coupled with multiple column switching and micro thermal conductivity detectors, appears to offer significant advantages over MS systems in this application. A Commercial-Of-The-Shelf GC system which meets 90% of our measurement needs has been identified and is being procured. As a stand-alone process GC transmitter, this system will offer matrix independent analysis in a robust field-mountable design that will be modified for analysis optimization, and later for weight reduction, and vibration resistance.

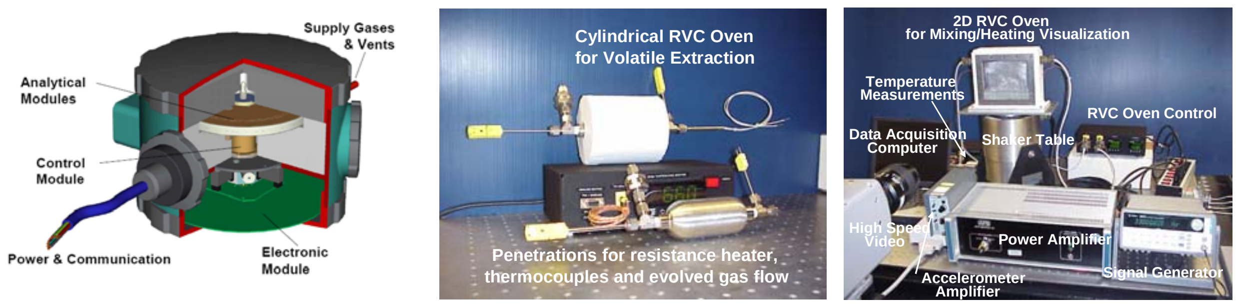


FIGURE 3. Gas Chromatograph and Breadboard RVC Oven

Regolith Oxygen Extraction (ROE) Demonstration Module

If water is present in the permanently shadowed craters of the lunar poles in usable and accessible concentrations, then large quantities of oxygen are easily available for future use at that site of exploration. However, at other locations on the Moon, or if water is not present, a different method for obtaining oxygen is required. The Moon is 45% oxygen (O_2) by mass, but it is in the form of metal and non-metal oxides and silicates. A recent study by the Colorado School of Mines (CSM) for JSC estimated the cost of taking each kilogram to the lunar surface at $90,000 per kilogram, the mass of the crewed ascent vehicle with propellant at 11,700 kilograms, the mass of the ascent propellant at 6,600 kilograms, and therefore the cost of taking the ascent propellant could be $594 M.[24] Producing the oxygen portion of the ascent propellant could end up as a huge cost savings.

Numerous studies have been performed on lunar ISRU production process options for extracting the oxygen from lunar regolith[25, 26]. Most laboratory efforts have focused on three methods; H_2 reduction of ilmenite and pyroclastic glass[27, 28, 29, 30], carbothermal reduction of lunar silicate[31], and molten silicate electrolysis[32]. Based on a review of many of the known methods for oxygen production and researching past studies on the subject, the following processes and organizations have been selected as candidates for study in the first year with one option to be pursued for the remainder of the project. The ROE requirements each design team must work toward are: i) ≥ 5.0 grams of oxygen produced per operation cycle, ii) ≥ 2 operation cycles, iii) < 80.0 watts peak power, iv) < 10.0 kilograms system mass, and v) < 15.0 liters system volume.

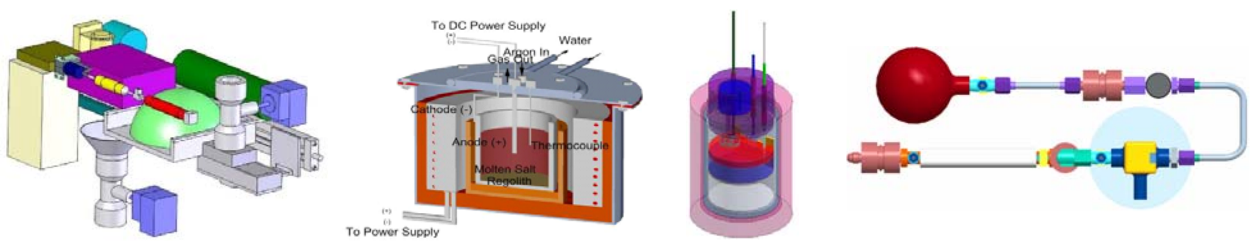
Carbothermal Reduction (ORBITEC): The Carbothermal Reduction of lunar silicate effort (Figure 4a) is building on ORBITEC's Carbothermal Reduction Processing System hardware and experience[33]. Preliminary testing utilizing various local heating methods in the presence of methane have demonstrated cracking portions of JSC-1 simulant to provide carbon dioxide and hydrogen. A catalytic reactor and water electrolysis allow the system to yield an end product of oxygen. The plan for ROE is to take the carbothermal process up to water electrolysis to demonstrate the technologies of this process that must be demonstrated on the moon to gain confidence for follow-on missions.

Electronic Reduction of Lunar Regolith in Molten Salt (CSM): The CSM ROE method of the Electronic Reduction of Lunar Regolith in Molten Salt (Figure 4b) will investigate a proven process in industry for producing titanium which has the by product of oxygen. CSM has begun testing and is making progress on a furnace design scaled down from industry practices to the ROE size. The molten salt electrolysis could lead to a high oxygen yield process option as system design challenges such as recovery of the salt post-electrolysis are addressed.

Magma Electrolysis (Boeing): The Magma Electrolysis (Figure 4c) effort will leverage past magma furnace development and testing experience[31]. The yield of the magma electrolysis process is limited by the operating temperature and the engineering challenges associated with the higher operating temperatures. Boeing is addressing these challenges to identify how hot and therefore how many regolith phases to attempt to melt to gather oxygen.

Hydrogen Reduction (Johnson Space Center): The Hydrogen Reduction (Figure 4d) effort will utilize decades of research, development and testing experience at JSC and via JSC funded contracts and grants. Hydrogen reduction offers a simple approach for an oxygen extraction demonstration but the potential for a lower oxygen yield is being weighed against any increased complexity of the other methods. JSC has produced a preliminary system design for ROE that will output water utilizing Earth originated hydrogen and will begin testing this system in the near future.

After completing trade studies and laboratory tests, the RESOLVE project will select one ROE oxygen production method based on several factors including: the energy required to perform the oxygen production, the expected oxygen yield of the process (grams of oxygen produced per 100 grams of regolith), ROE unit mass, and intangibles such as system complexity and estimated chance of success. A decision to have separate or integrated RVC and ROE modules will be made in Phase I as the benefits of one furnace versus two must be weighed against the feasibility of a common design.



(a) (b) (c) (d)

FIGURE 4. ROE Concepts from ORBITEC, CSM, Boeing, & JSC

Lunar Water Resource Demonstration (LWRD) Module

The ability to separate, purify, and decompose water into oxygen and hydrogen is a critical capability for lunar and Mars in-situ resource utilization, as well as life support, regenerative fuel cell power, and water-based propulsion system applications. For the RESOLVE unit, water may be obtained from either the RVC or the ROE modules. The primary objective of the Lunar Water Resource Demonstration (LWRD) module proposed is to develop an integrated water & hydrogen separator/purification and water electrolyzer system that can operate effectively in the extreme lunar environment. Since water and hydrogen are resources of significant interest, the LWRD module will also include methods for collecting and separating these two resources from other volatiles. Methods that are under evaluation are molecular sieves, adsorption beds, metal hydrides, membranes, anhydrous salts[34], and thermal phase separation with and without inert purge gases. The characteristics of these are briefly discussed with respect to their interaction with hydrogen and/or water and the selectivity for the process. Breadboard systems for some methods have been built and testing is in progress to determine the most appropriate method for the LWRD module. The evaluation parameters include: (1) capture efficiency, (2) selectivity, (3) weight, (4) mass, (5) power, (6) reproducibility, and (7) reliability.

Water Capture: When absorbent beds use molecular sieves there are two properties that are important, the pore size of the sieve and the heat of adsorption. If the pore size is sufficiently large for the gas molecules to reach the inner surfaces, then the heat of adsorption determines which molecule is preferentially absorbed. Since water has the highest heat of adsorption among know lunar volatiles, it will be preferentially absorbed. If the concentration of water is insufficient to occupy all of the available sites, then other gases will be adsorbed, which limits the selectivity. However, with careful control of the desorption process it may be possible to selectively remove adsorbed gases that are less strongly held before water is removed. Similar behavior is found with silica gel and other physical adsorbents, but anhydrous salts that form hydrates uniquely capture water. However, there is concern with some of the anhydrous salts that are deliquescent, since they can absorb enough water to dissolve the salt. Another method that can be used to capture water and other volatiles is to freeze them, and then selectively melt or vaporize the captured materials.

Selection of an anhydrous salt that will efficiently capture and release water is a two step process, which starts by examining the differential scanning calorimeter/thermal gravimetric analyzer (DSC/TGA) scans of the dehydration of the hydrated salts. This provides information on the weight loss and the associated energy as a function of temperature. The target is to select hydrated salts that release their water at temperatures above 100°C so the salt will not be dissolved by the released water. The second factor is the percent water released, which gives the capacity of water that can be captured. These data have been collected for over 30 different hydrated salts and data are now being collected on the how these salts capture and release water. A test bed that measures the rate of water capture, breakthrough, and capacity used the test cell shown in Figure 5. In addition, the physical characteristics of the anhydrous salt are examined to see how their shape and size changes as they are recycled. This information will be used to select the best anhydrous salt to capture and purify water generated from the RVC. These results will be used to compare the performance of the anhydrous salt capture technique with other water methods.

A water vapor cold trap is under construction that will be used to replace the anhydrous salt test cell so a direct comparison between the capture performance of anhydrous salt and a cold trap can be made. The cold trap will use liquid nitrogen to simulate a lunar cooling system. Once information about the capture of water is collected, then other known lunar volatiles will be added to water vapor to test the selectivity of the freezing method.

These methods, freezing and anhydrous salts, will be tested first and if satisfactory results are obtained then other methods to capture water will not be examined, but if the results are in question additional methods discussed above will be examined.

Hydrogen (H_2) Capture: Sandia National Laboratories compiled the Hydride Materials Data Base in 2002 that contains over 2700 entries. This database was examined and 47 possible candidates to capture hydrogen generated by the RVC based on an initial temperature of 110°C at 5 bar and 300 ^oC desorption were identified. Of the 47 systems initially identified Mg/MgH_2, Mg_2Ni Mg2NiH4, $ZrNi/ZrNiH_{2.8}$, and $Pd/PdH_{0.77}$ were selected for testing. The first system, ZrNi was examined in the test fixture shown in Figure 5 and found to be very promising. It self activates at H_2 pressures less than 1 bar at room temperature and degases at 160 ^oC to 250 ^oC. Experimentation has revealed that the sorption process at 110 ^oC is sluggish but occurs rapidly at 150 ^oC with extensive conversion of ZrNi to $ZrNiH_{2.8}$. Resistance to flow of gas through the reactor increased with sorption and decreased with desorption, suggesting that the specific volume of the ZrNi increases upon hydride formation. The additional alloys listed above will be tested to determine the most effective for this application based on the weight percent hydrogen that can be captured and released, release temperature and pressure, and resistance to other known volatiles.

Hydrogen can also be permeated through a palladium membrane and captured on the metal hydride as a way to eliminate problems with other volatiles that would not be captured in the water capture system. These volatiles could be trapped in the voids in the metal hydride bed if they are not actively removed. However, the current system design has an evacuated chamber to help remove these volatiles.

Electrolyzer: An alkaline electrolyzer has been selected for this application because it does not have to be keep wet with water. Two electrolyzers have been ordered and one has been received and is currently undergoing testing. The goal is to demonstrate that the unit can electrolyze water to dryness and then restart when water is added. Operating power requirement, cell weight, physical size, production rate, and stability of the anode will be determined.

Water Visualization: A water visualization cell will be prepared to capture water from the anhydrous salt bed when it is desorbed or the water is released for the cold trap so it can be photographed. A small camera will be mounted in the cell or a window will be positions so an onboard camera (ERPC) can view the captured water.

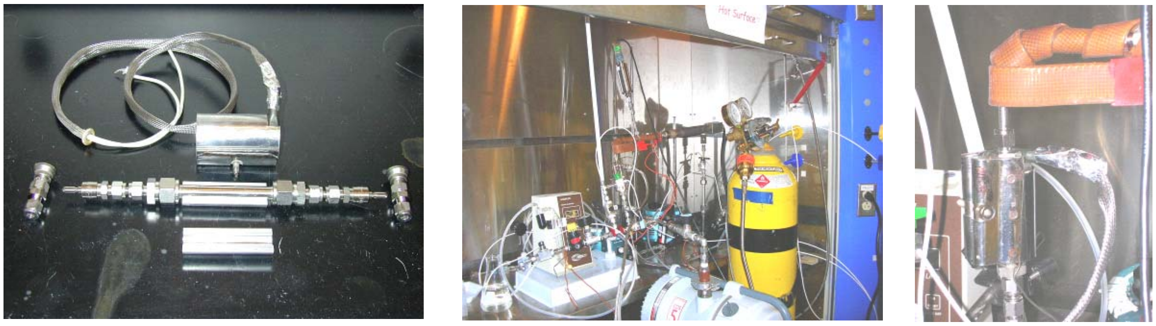


FIGURE 5. Hydrated Salt and Metal Hydride Characterization Test Hardware

RESOLVE Integration

To meet the self-imposed target mass and power (30 kg and 100 watts), integration of the five modules will be critical. At the start of RESOLVE, each module was purposefully analyzed as a stand alone unit even though common hardware and sensor options were known to be possible. This approach was utilized to ensure that all module requirements could be met. As time went on and concept designs were created based on initial requirements, examination of possible function and hardware integration across modules was performed. Figure 6 is an example of a conceptual integrated unit for RESOLVE. In this example, the heating chambers for the RVC and ROE are combined into a single unit. The Gas Chromatograph from the RVC is tied into both the combined volatile extraction/ROE chamber and the sample crusher from the EBRC to ensure that volatiles released during sample processing/crushing and heating/processing are measured. Exhaust gases from the EBRC crusher and the RVC/ROE chamber are routed to the water and hydrogen adsorption beds of the LWRD. Also shown is the CHAMP/MMRS from the ERPC viewing a window in the EBRC crusher. The integrated schematic shows a zero fault tolerant design. A reliability assessment will be performed in Phase II to balance the mission risk reduction with increased redundancy against the added cost and mass.

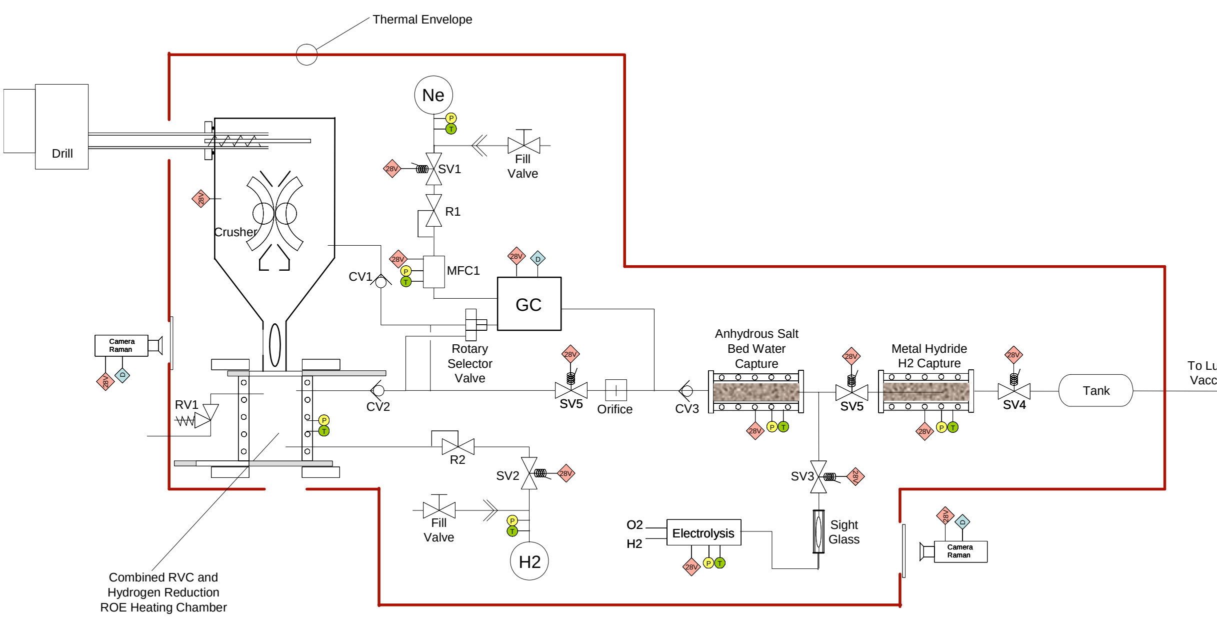


FIGURE 6. Conceptual Integrated RESOLVE unit

SUMMARY

The purpose of the Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) project is to develop and integrate an experiment package that can perform the following objectives; (1) obtain "Ground Truth" data for resources at lunar pole; (2) obtain bulk and fine-grained regolith characteristic and environment data; (3) extract and collect volatiles from regolith; (4) produce oxygen from regolith; and (5) perform a hydrogen/water resource processing demonstration after it has been evolved and collected. To meet these objectives and goals, five modules are being developed to integrate into a single polar resource characterization and ISRU demonstration unit. The integrated RESOLVE experiment package is being designed and built to eventually operate under simulated lunar permanently shadowed crater environmental conditions (TRL 6). The RESOLVE project was initiated through the Exploration Systems Mission Directorate (ESMD) Intramural Call for Proposals (ICP) under the Technology Maturation Program and was officially started on Feb. 1, 2005. RESOLVE is currently in Phase I (1st year) of a possible four year project (Phase II includes the 2nd through 4th years). In Phase I, work to date has focused on evaluating experiment options, validating critical experiment features, and providing a logical development plan with credible cost and development risk for Phase II. The RESOLVE project is being led by NASA JSC and supported by a small team consisting of experts in lunar resource, flight hardware, terrestrial mining, and ISRU processing from KSC, GRC, MSFC, & JPL, academia (Univ. of Hawaii & Tennessee and Colorado School of Mines), and industry (NORCAT, ORBITEC, & Boeing).

RESOLVE hardware is uniquely designed to provide critical data and experience for subsequent ISRU missions to the Moon and Mars. The drill/core capture mechanism (developed by NORCAT) minimizes volatile loss and maximizes knowledge of resource and bulk regolith properties. The optical imaging/mineralogical instrument (developed by JPL) provides both local terrain/navigation imaging as well as fine grain regolith characterization. These capabilities with the hydrogen, water, and oxygen extraction processes (developed by KSC, GRC, and JSC) can provide early data and expertise for subsequent efforts, including characterization of water resources on Mars.

Significant progress has been achieved since the start of the project (2/1/05). Lunar polar permanently shadowed crater environmental and regolith property requirements have been defined for RESOLVE design and testing. A representative physical/mineralogical lunar polar regolith simulant has been identified and production of the simulant has started. Breadboard hardware has been design, built, and tested for each of the five RESOLVE modules to demonstrate critical features of the Phase II design. Integration of the five modules has begun into an integrated design and operation package that will be evaluated at the bench-top level by the end of Phase I.

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