NASA In-Situ Resource Utilization (ISRU) Project And Its Linkage To Lunar Science

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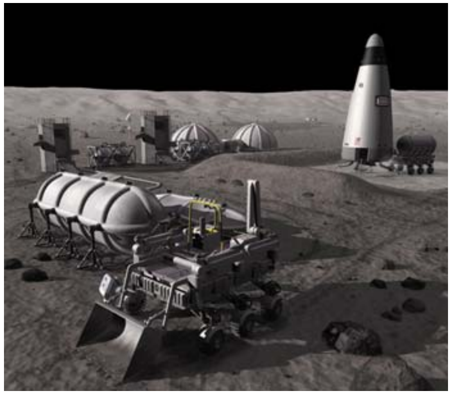
ISRU: Architecture Impacts & Drivers

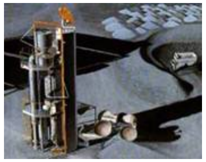


- **ISRU is a critical capability and key implementation of the VSE**
  - Enables the concept of “living off the land”
  - Has the potential to substantially reduce lunar downmass and logistics
  - Has the potential to further increase lunar downmass if LSAM can be fueled from lunar ISRU
  - **ISRU Objectives rated highly as a result**
- **At the same time, ISRU on the Moon is an unproven capability for human lunar exploration and can not be put in the critical path of architecture until proven**
  - Need to perform demonstrations to increase confidence in ISRU
  - Need to perform hydrogen/water resource prospecting ‘early’ for this resource to influence human exploration
- **Therefore, ISRU (as an end in and of itself) will need to take incremental steps toward the desired endstate**
  - Starts with gaining knowledge in Precursor missions
  - Continues with finding the hydrogen (location, form, concentration, etc)
  - Begins small scale demonstration
  - Hits the easy stuff first, like oxygen
  - Architecture is designed to be completely independent from ISRU, just in case it doesn’t pan out initially
- **Architecture is designed to be open enough to take advantage of ISRU from whatever source when available**
  - Scavenge spent LSAM tankage
  - Use ECLSS closed-loop byproducts
  - Design LSAM to have the capability to fuel at the Moon (but don’t count on it)
  - Practice and demonstrate ISRU processes and techniques at every step

Objectives of Lunar ISRU Development & Use

- **Identify and characterize resources on Moon** (especially polar region) that:
  - Can strongly influence mission phases, locations, and element designs to achieve maximum benefit of ISRU
  - Is synergistic with Science and space commercialization objectives
- **Demonstrate ISRU** concepts, technologies, & hardware that reduce the mass, cost, & risk **for future Mars missions**
  - Excavation and material handling & transport
  - Volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems for oxygen and fuel production
  - Cryogenic fluid storage & transfer
  - Metal extraction and fabrication of spare parts
- **Use Moon for operational experience** and mission validation **for Mars**
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables *(propellants, life support, power, etc.)*
  - Landing crew with pre-positioned return vehicle or 'empty' tanks
  - 'Short' (<90 days) and 'Long' (300 to 500 days) Mars surface stay dress rehearsals
- **Develop** and evolve lunar **ISRU capabilities** that *enable* exploration capabilities **from the start of the Outpost** phase
  - ex. **Human and robotic hoppers for long-range surface mobility and global science access**; power-rich distributed systems; enhanced radiation shielding, etc.
- **Develop** and evolve lunar **ISRU capabilities** to support sustained, **economical space transportation**, presence on Moon, **and space commercialization** efforts
  - Lower Earth-to-Orbit launch needs
  - Enable reuse of transportation assets and single stage lander/ascent vehicles
  - ➢ **Lower cost to government thru government-commercial space commercialization initiatives**

ISRU Capabilities for Human Lunar Exploration

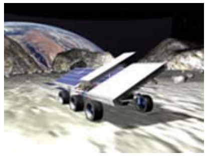


Pre-Outpost

- Determine type, amount, and location of possible resources of interest (i.e. ilmenite, water, concentrated volatiles, etc.) – try to link to Science objectives
- Perform proof-of-concept and risk reduction demonstrations to certify ISRU capabilities for use at the Outpost - link to commercialization of space if possible
- Perform site characterization of topography, subsurface, and lighting conditions

Initial ISRU Capabilities to be pursued during early Outpost (first 5 years)

- Pilot-scale oxygen production, storage, & transfer capability (replenish consumables)
- Pilot-scale water production, storage, & transfer capability – assuming hydrogen source/water is accessible
- Demonstration of In-situ fabrication and repair demonstration
- Possible ISRU Capability under evaluation - Excavation & site preparation (i.e. radiation shielding for habitats, landing plume berms, landing area clearance, hole or trench for habitat or nuclear reactor, etc.)



Mid-Term ISRU Capabilities - Exploration growth ("Hub & Spoke")

- Propellant production for LSAM
- Consumables for Pressurized rover or Hopper from Outpost
- Nitrogen demonstration (if accessible and available)
- Construction and fabrication demonstrations

Possible Long-Term Lunar Capabilities (Settlement)

- In-situ manufacturing and assembly of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- In-situ life support – bio support (soil, fertilizers, etc.)
- Power generation for Moon and beyond: beaming, helium-3 isotope (^{3}He) mining, etc.

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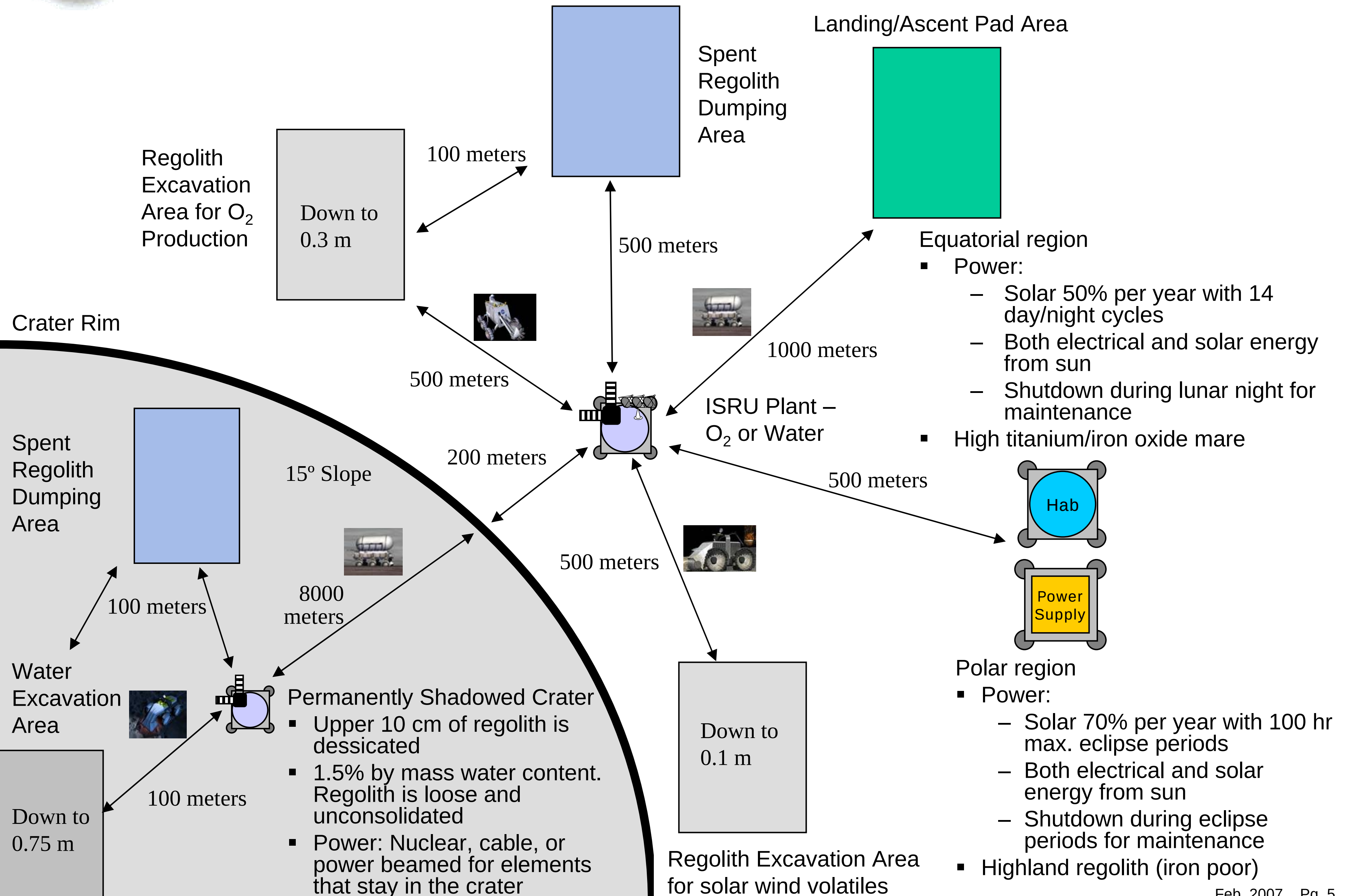
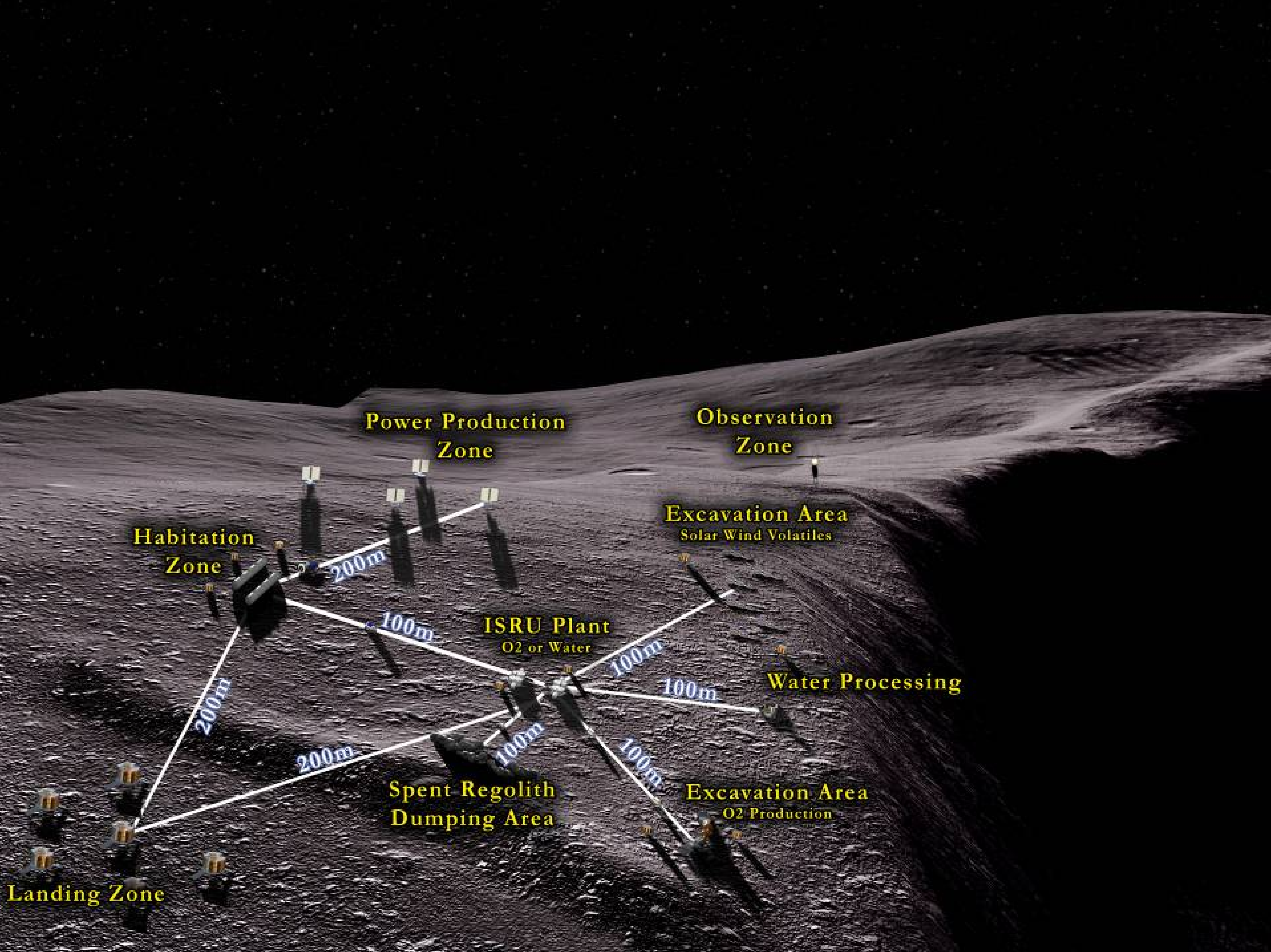
ISRU Level 0 Mission Assumptions

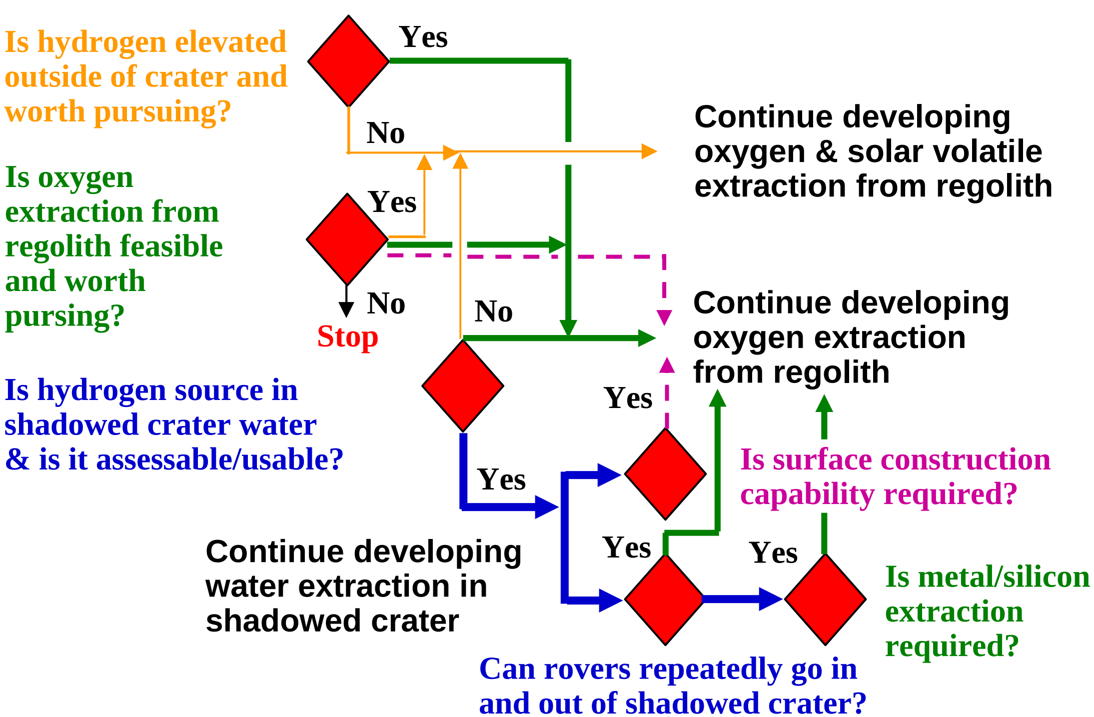


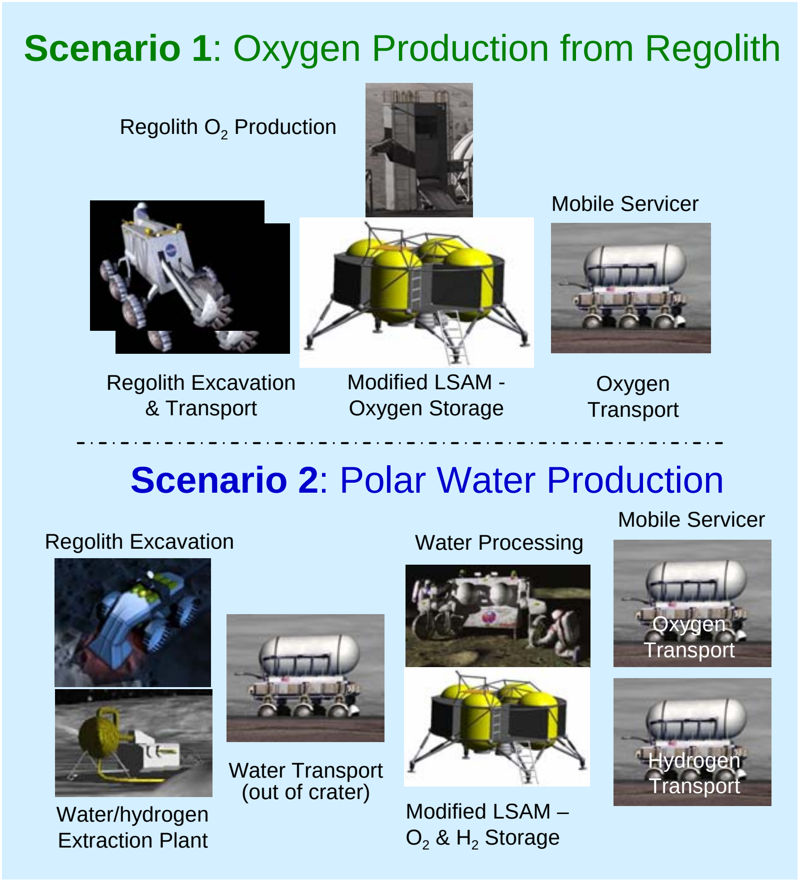

Power Production
Zone
Observation
Zone
Habitation
Zone
Excavation Area
Solar Wind Volatiles
200m
100m
ISRU Plant
O2 or Water
100m
100m
Water Processing
200m
200m
100m
100m
Spent Regolith
Dumping Area
Excavation Area
O2 Production
Landing Zone

ISRU Capability Scenarios

- **Four 'Scenarios' examined for ISRU based on potential resource and usage options for human lunar exploration**
  - Each Scenario identifies and sizes the elements needed to collect, process, store, and deliver the ISRU products for use
  - 4 production rate point designs developed to allow understanding of ISRU element mass, power, and number of elements vs usage/need rates for each Scenario

- **Scenario 1**: Oxygen Production from Regolith
- **Scenario 2**: Polar Water Production
- **Scenario 3**: Volatile Extraction from Regolith
- **Scenario 4**: Lunar Terrain Modification





Lunar ISRU Oxygen Production Demo & Deployment Roadmap (Min Risk Approach)

FY06 FY07 FY08 FY09 FY10 FY11 FY12 FY13 FY14 FY15 FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23

Outpost Site Selection
Early
Nominal
Early LSAM PDR
Nominal LSAM CDR

Crewed Missions
LSAM Flight Test
2024 Closed Loop ECLSS
2025 Propellant Production

Phase 1 Proof-of-concept
Phase 2 Risk Reduction for Outpost
Outpost Deployment

Rim Lander to Primary Outpost Site

Φ A | Φ B | Φ C | Fab | ATLO

A. ISRU O_2/Volatile Proof-of-Concept

O1. Measure volatiles at crater rim to compare with LRO & Lunar Prospector data

Secondary Objectives

O2. Process polar regolith to extract oxygen

O3. Public Outreach: Concrete demo to public that VSE is going beyond Apollo to learn to "live off the land"

Mission A. Demonstrates

- **ISRU**: Volatile concentrations outside of crater & Oxygen production is feasible
- **Science**: Volatile measurements & hardware applicable to polar crater mission to search for water (reduces mission risk)
- **Mars Forward**: volatile measurement & water prospecting hardware can be modified for Mars water prospecting mission

Rim Lander/Rover

Φ A | Φ B | Φ C | Fab | ATLO

Surface Operation

C. ISRU O_2 Production Risk Reduction

O4. Demonstrate relevant regolith excavation and transport techniques for oxygen production

O5. Demonstrate oxygen production at scalable rate for extended period of time

O6. Demonstrate coordinated, semi-autonomous excavation and O_2 production for min. of 6 months.

O7. Demonstrate oxygen liquefaction and boiloff control of ISRU produced oxygen

Mission C. Demonstrates

- **ISRU**: Oxygen production rate for EVA usage anywhere on Moon
- **ISRU/Mobility**: Common mobility platform for ISRU and crew aid
- **ISRU/Propulsion/EVA**: Long-term liquid oxygen storage for LSAM and cryo PLSS
- **Mars Forward**: Water electrolysis and oxygen liquefaction & storage applicable to Mars ISRU

Outpost ISRU Deployment

Φ A | Φ B | Φ C | Fab | ATLO

Outpost: O_2 Production & Storage (5 MT/yr rate)

- 1 to 3 rover/excavators
- Regolith processor for O2 production
- Oxygen liquefaction & storage based on modified LSAM
- Cryogenic fluid pallet for O2 transfer from storage tank

Lunar ISRU Water Demonstration & Deployment Roadmap (Min Risk Approach)

FY06 | FY07 | FY08 | FY09 | FY10 | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23

Outpost Site Selection
- Early
- Nominal

- Early LSAM PDR
- Nominal LSAM CDR

Crewed Missions

LSAM Flight Test

2024 Closed Loop ECLSS
2025 Propellant Production

Legend:
- Phase 1 Proof-of-concept
- Phase 2 Risk Reduction for Outpost
- Outpost Deployment

LRO/LCROSS

Rim Lander to Primary Outpost Site

Φ A | Φ B | Φ C | Fab | ATLO

A. ISRU O_2/Volatile Proof-of-Concept

O1. Measure volatiles at crater rim to compare with LRO & Lunar Prospector data

Evaluate need for Shadowed crater mission

Is hydrogen source in high concentration outside of the shadowed crater?

Yes

No

Lander/Rover Crater Mission

Φ A | Φ B | Φ C | Fab | ATLO

Surface Operation

Mission B. Demonstrates

- **ISRU/Science**: Determines what, where, and how much the hydrogen source is, how much energy it takes extract, and geo-technical properties of regolith
- **Mars Forward**: volatile measurement & water prospecting hardware can be modified for Mars water prospecting mission

B. Polar Resource Characterization

W1. Perform resource prospecting in shadowed crater
- Determine form, concentration, & spatial distribution of H_2/water
- Determine mineral/geotechnical properties for pilot plant design
- Begin 3-D resource mapping

Is hydrogen source assessable in the shadowed crater?

Yes

Lander/Rover Crater Mission

Φ A | Φ B | Φ C | Fab | ATLO

Surface Operation

D. Polar Water Extraction & Crater Risk Reduction – Subscale Outpost Capability

W2. Demonstrate excavation and water extraction at scalable rate in shadowed crater

W3. Demonstrate coordinated, semi-autonomous operation for min. of 6 months.

W4. Demonstrate water removal from shadowed crater

W5. Demonstrate repeated entry and exit from crater

Mission D. Demonstrates

- **ISRU**: Demonstrates feasibility of extracting polar resource
- **ISRU/Mobility**: Common mobility platform w/ Mission B but nuclear power required
- **Mars Forward**: Excavation and extraction techniques applicable to Mars water extraction from soil

Outpost ISRU Deployment

Φ A | Φ B | Φ C | Fab | ATLO

Outpost: Water Extraction in Crater & Processing (1 MT/yr rate)
- 1 to 2 rover/excavators (in crater)
- Regolith processor (in crater) for water extraction
- Crater entry/exit vehicle to transfer water to O_2 Processor
- Water electrolysis unit as part of O_2 Processor

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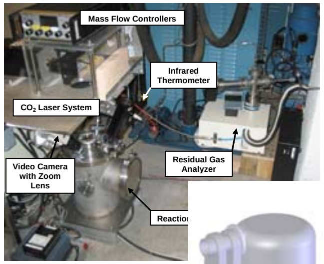
Lunar Oxygen Production Overview

Production rate of 1 MT oxygen (O_2) & 1 MT water per year is baselined for the initial Outpost (2023) with buildup to 10 MT O_2 per year by 2027 with fuel:

- **Initial capability supports EVA and habitat life support needs**
- **Build-up rate supports oxygen need for two LSAM ascent vehicles, EVA consumables, and habitat/life support backup**



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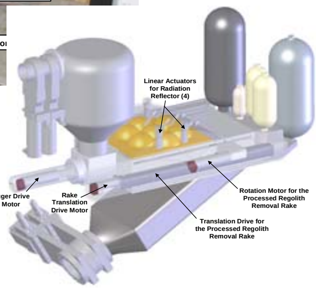
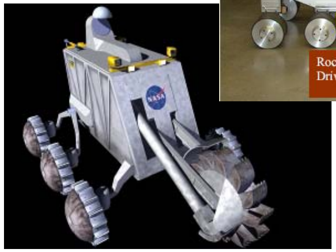
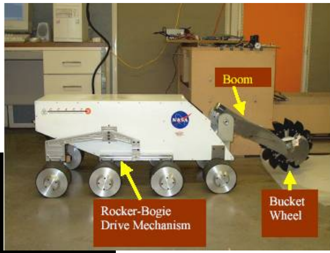


- **Oxygen Production Plant**
  - Three process types currently under laboratory development and evaluation
    - Hydrogen Reduction of Regolith (iron oxide)
    - Carbothermal Reduction (with Methane or Carbon Monoxide)
    - Electrowinning of Regolith (Salt or Molten Electrolysis)
  - Excavation rates required for 10 MT O_2/yr production range based on extraction efficiency of process selected and location
    - Hydrogen reduction at poles (~1% extraction efficiency): 150 kg/hr
    - Carbothermal reduction (~14% extraction efficiency): 12 kg/hr
    - Electrowinning (up to 40%): 4 kg/hr

- **Regolith Excavation System**
  - Laboratory tests showed high excavation rates up to 150 kg/hr for small bucket wheeled vehicle (<50 kg)
  - Order of magnitude higher excavation rate capability above processing feed rate easily covers extra time required for traverse and maintenance
  - Flight vehicle estimated in the **100 to 200 kg range** to ensure excavation stability, support hardware allocations, and on-board power system even though excavation rate is greater than required

Courtesy of Colorado School of Mines





Mass of ISRU hardware required to produce 8 to 10 MT of oxygen per year is <2000 kg.

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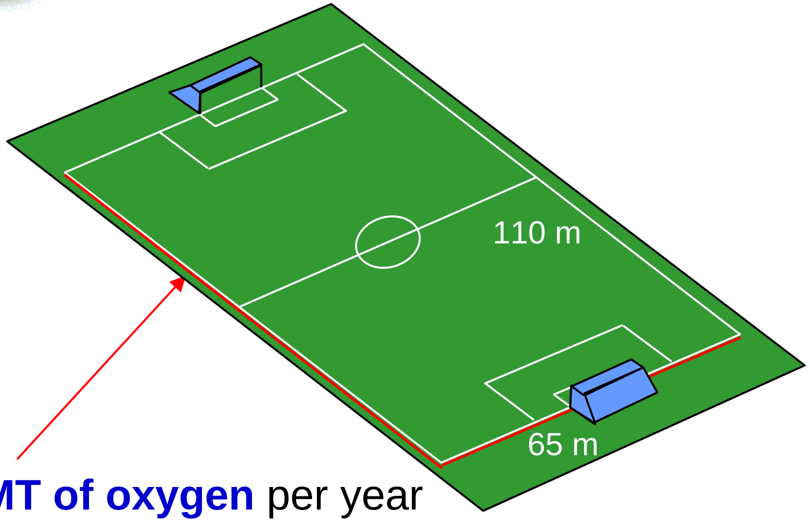
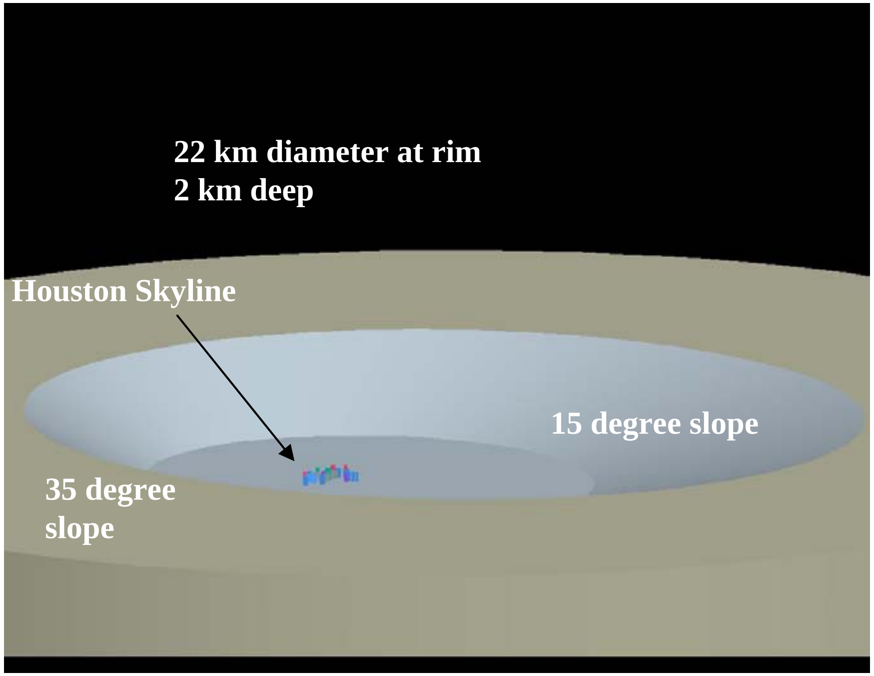
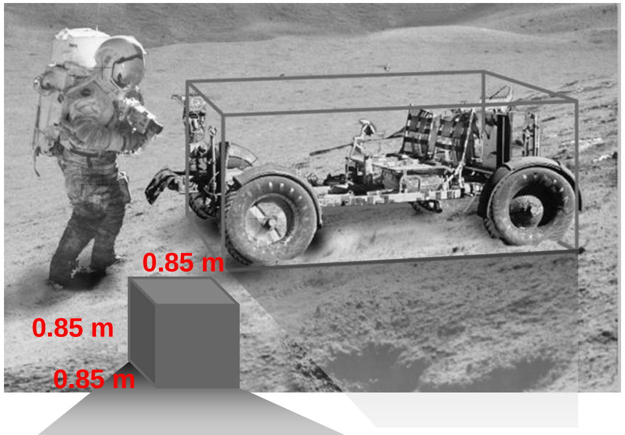
ISRU Analogies



10 MT of oxygen per year requires excavation of a soccer field to a depth of **0.6 to 8 cm!**
(1% & 14% efficiencies)

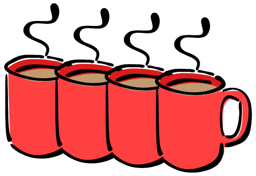
Model of Dawes Crater (Shackelton analog)



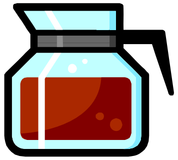


Volume equivalent to 1 Metric Ton of lunar regolith

Volume equivalent to 20 Metric Tons of lunar regolith



10 MT of oxygen per year requires a regolith excavation rate of
~**1 cup per minute!** (5% efficiency - 50% daylight)
~**4 cups per minute!** (1% efficiency - 70% light)
(worst case)

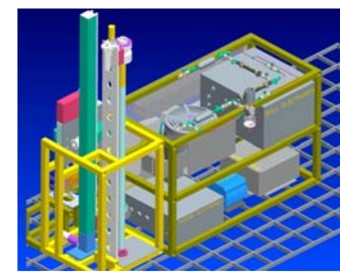


300 MT of oxygen per year requires a regolith excavation rate of
~**10 cups per minute**!
(14% efficiency - 70% time-polar region)

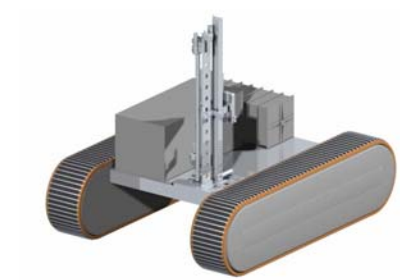
Lunar Volatile & Water Resource Overview

- Besides oxygen, in-situ availability of water and hydrogen is of significant interest for human exploration
  - Life support, crew drinking/cleaning and degree of water processing required
  - Extra-vehicular activity (EVA) suit cooling
  - Oxygen and hydrogen from water for propulsion and regenerative fuel cells; also easily transferable to other locations for processing (orbital depots)
  - Radiation shielding

- Elevated hydrogen source most likely in permanently shadowed craters at lunar poles raising significant acquisition and processing issues
  - Extremely cold-vacuum environment (40 to 100 K)
  - Potentially at bottom of deep craters (4 to 8 km with 15 to 30 degree slopes) has impact on power and surface mobility
  - Transition for sunlit to cold environment has impact on thermal control design
  - Mixtures of water and regolith at low temperatures impacts excavation force and design

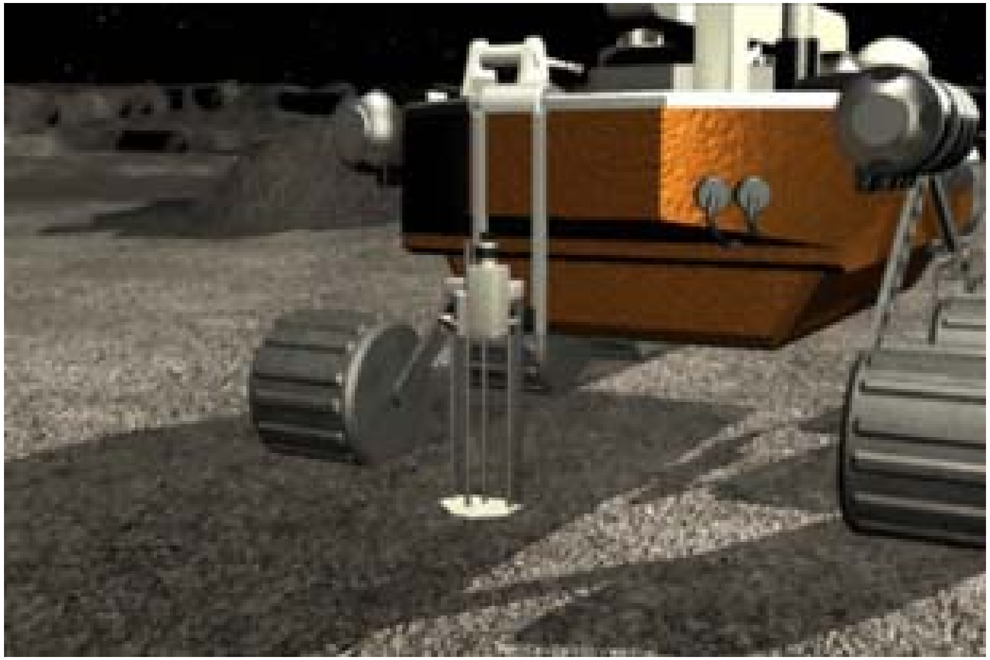


- Currently developing resource acquisition, processing, and characterization hardware for possible use in future LPRP mission for science and exploration to determine:
  - Regolith properties for future excavation and processing systems
  - Volatile constituents, amounts, and distribution
  - ISRU related hardware performance:
    - Seals for multiple regolith processing
    - ‘Large’ amounts of regolith processed at once
    - Oxygen extraction from regolith



RESOLVE

Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



RESOLVE Objectives

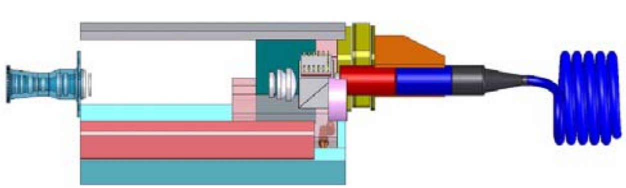
Resource Characterization	1	**Determine form and concentration of hydrogen in permanently shadowed regions (detected by Lunar Prospector)**	*Science - Resource Focused*
	2	Determine other volatiles available	
	3	Determine grain size distribution and morphology of regolith	
	4	Determine quantity of which volatile(s) are evolved by excavation & crushing	
	5	Determine chemical/mineralogical properties	
In-Situ Resource Utilization Demo	6	**Determine bulk excavation related physical properties of 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 spatial distribution of resources	Rover required
	G3	Demonstrate scalable extraction/processing techniques	
	G4	Demonstrate scalable oxygen production technique	

RESOLVE Overview

- **RESOLVE will incorporate five experiment modules from three NASA institutions; JSC, KSC, JPL**
  - **Support from GRC & MSFC**
  - **Drill and excavation expertise from Northern Centre for Advanced Technology**
  - **Significant university and Lunar science expertise**
- **JSC will integrate the modules into engineering & flight-like prototype units**

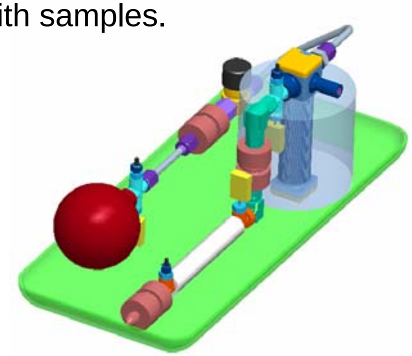
The five RESOLVE modules are:

- **EBRC - Excavation and Bulk Regolith Characterization (KSC/NORCAT/CSM)**
  Provide capability of extracting samples of regolith down to 1-2 meter and determine geo-technical characteristics of the regolith.



- **ROE - Regolith Oxygen Extraction (JSC/GRC)**
  Demonstrate the ability to chemically extract oxygen from the regolith samples.

- **ERPC - Environment and Regolith Physical Characterization (JPL)**
  Determine the particle size, shape, color, and chemical characteristics of regolith samples and the regolith temperature in the permanently shadowed crater



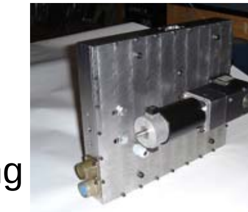
- **RVC - Regolith Volatile Characterization (KSC/GRC)**
  Provide capability of evolving and measuring volatiles from regolith samples to determine the form and concentration of hydrogen-bearing molecules in shadowed regions near the lunar poles. Also, determine other volatiles of interest.

RESOLVE Target Design

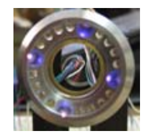
- **Mission Design Life = 7 days in shadowed crater**
- **Mass = 30 kg**
- **Max. Power; 100 Watts**

- **LWHRD – Lunar Water-Hydrogn Resource Demonstration (KSC)**
  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

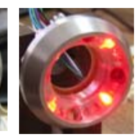
RESOLVE Accomplishments – Top Level



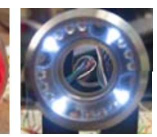
- **Excavation and bulk regolith characterization**
  - Drill prototype including core capture device, drive electronics/controls testing in frozen ground (2/06)
  - 1st generation crusher designed, built, and tested with samples of varying hardness
  - Thermal shock testing of first generation drill bit
  - Mechanical Design of Engineering Breadboard Unit Complete



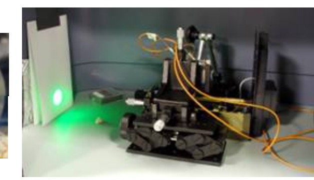
UV LEDs illuminated



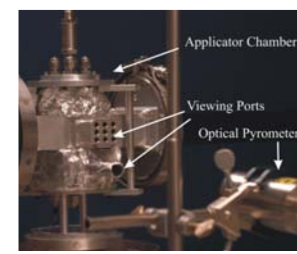
Red LEDs illuminated



White LEDs illuminated



- **Environment and Regolith Physical Characterization**
  - Lens cell designs complete and glass selected
  - Illumination subsystem design completed and tested
  - Integrated optical and Raman spectroscopy capability tested and verified



- **Regolith Volatile Characterization (RVC)**
  - Heating Chamber
    - 1st generation heating chamber built and tested to investigate vibro-fluidization amplitude/frequency operation space. Included vacuum.
    - Ran series of tests combining vibratory fluidization with microwave heating.
    - 2nd generation of heating chamber incorporating small light-weight vibratory fluidizer and drive electronics designed
  - Volatiles Identification
    - GC successfully converted to operate on Neon instead of helium
    - Highly accurate water vapor generator designed and built. Allows a calibrated “source” for GC investigation
    - Full spectrum of water detection signatures developed over range of GC temperatures from 60 C to 110 C

Global Lunar Strategy Objectives: Prioritized-Top 40

Overall Rank	Objective ID Number	Category	Short Title
1	mCAS2	Crew Activity Support	EVA Suit
2	mLSH3	Life Support & Habitat	Closed Loop ECLSS (physiochemical)
3	mEHM1	Environmental Hazard Mitigation	Radiation Shielding (Background & Solar Flares)
4	mLSH1	Life Support & Habitat	Habitation Systems
5	mHH2	Human Health	Lunar Environment Effects on Humans
6	mOPS1	Operations, Test & Verification	Human Surface Ops (Make EVA easier)
7	mHH1	Human Health	Fundamental Biological & Physiological Studies
8	mOPS10	Operations, Test & Verification	Lunar Repair Techniques
9	mPWR1	Power	Power Generation, Storage, & Distribution
10	mHH3	Human Health	Lunar Health Care
11	mPE2	Program Execution	Exploration Strategy
12	mTRANS2	Transportation	Autonomous Lander
13	mEHM2	Environmental Hazard Mitigation	Dust Mitigation Techniques
14	mCAS3	Crew Activity Support	Human Machine Partnership
15	mPE6	Program Execution	Affordability & Sustainability
16	mOPS9	Operations, Test & Verification	Crew-Centered Control
17	mCOM1	Communications	Scalable Communications
18	mHH4	Human Health	Reduced Lunar Habitation Pressure Effects
19	mLRU6	Lunar Resource Utilization	Tools, Technologies, & Systems for ISRU
20	mOPS3	Operations, Test & Verification	Mars Analog
21	mSM1	Surface Mobility	Surface Mobility for Crew & Cargo
22	mLRU7	Lunar Resource Utilization	Produce Propellants & Other Consumables
23	mLRU1	Lunar Resource Utilization	Characterize Lunar Resource Potential
24	mLRU3	Lunar Resource Utilization	Demonstrate ISRU Technologies
25	mPE7	Program Execution	Program Execution Flexibility
26	mPE3	Program Execution	Maximize Synergy
27	mTRANS3	Transportation	Cryo Fluid Management
27	mGEO8	Geology	Characterize Potential Resources
29	mOPS2	Operations, Test & Verification	Remote Training
30	mCAS5	Crew Activity Support	Teleoperations & Telepresence
31	mPE4	Program Execution	Emphasize System Performance
32	mGEO7-1	Geology	Characterize Lunar Volatiles
33	mSM2	Surface Mobility	Surface Mobility for Outpost
34	mENVMON1	Environmental Monitoring	Monitor Space Weather
35	mCAS4	Crew Activity Support	Autonomous Robotic Support for EVA & Long Range
36	mLRU9	Lunar Resource Utilization	Lunar Elements that Use ISRU
37	mNAV1	Navigation	GNC Lunar Capabilities
38	mENVCH3	Environmental Characterization	Characterize Surface Radiation Environment
39	mEHM4	Environmental Hazard Mitigation	Thermal Protection
40	mENVCH5	Environmental Characterization	Characterize Dust Environment

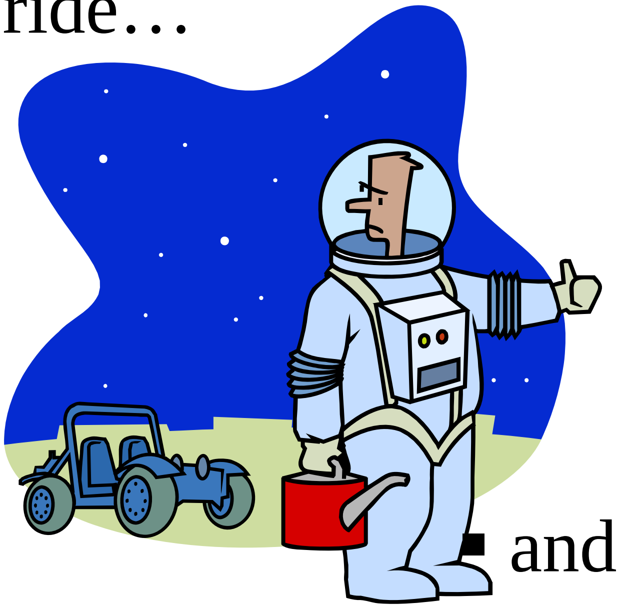
Overarching Objectives

Red = ISRU Objectives; Blue = Objectives Linked to ISRU Objectives

RESOLVE Status

- Hardware for Engineering Breadboard Unit (EBU) will be integrated and tested at JSC in late spring.
- The Materials Handling Section of RESOLVE will be integrated on a Rover for Field Demonstration tests in late 2007.
- With the Successful Completion of EBU the project will be enter the Flight Prototype Unit (FPU) Phase.
- FPU could be ready for environmental tests in FY 2009 (budget challenged)

- Looking for a ride…



- and we're not picky

Backup Slides

RESOLVE Requirement Highlights

RESOLVE Requirements
Understanding the Resources – Sample Extraction

- Shall extract samples from surface down to **1 meter deep**
  - Primary resource of interest is within top 1 meter of regolith
    - Orbital and surface neutron spectrometer for prospecting penetrates no deeper than 1 meter
    - Top 5 to 10 cm are most likely ‘dry’ (Lyman-alpha scattering & ‘gardening’)
    - Resources below 1 meter may be too difficult to extract ‘economically’
  - 3 drilling operations minimum; 10 drilling operations nominal
- Shall allow discreet analysis on regolith from **4 depth zones** (25 cm length - 1.5 cm diameter per segment)
  - Shall limit the amount of cross-contamination from zone to zone to <10%
  - This should allow adequate resolution for depth distribution and to determine overburden that must be dealt with in future large scale excavations
- Shall be designed to extract samples containing any water content from 0 to 100%
- Shall be designed to accommodate rocks in the excavation zone
- Shall capture loosely held volatiles during the extraction and transfer process to the maximum extent possible
  - A significant portion of the volatiles may be only loosely held mechanically. Understanding of this characteristic will influence future extraction methods.
- Shall crush the samples to particle sizes of <1mm and quantify volatiles evolved in the process
  - Allows complete quantification of volatiles released through mechanical agitation
  - Improves heat transfer/mixing in subsequent fluidized heating chamber
  - Avoids concerns with transferring and processing ‘ice-cemented’ hard fragments

RESOLVE Requirements

Understanding the Resources – Volatile Determination

- Shall detect, identify, and quantitate compounds that are evolved from the regolith into the gas phase headspace and that are present in concentrations above the detection limit of >0.5% by volume
  - Measure constituents (under 100 AMU) and amount of water & volatiles released
- Errors in the quantitative analysis of each compound shall not exceed 0.2% by volume of the total evolved gases or 10% relative of the specific gas identified, whichever is greater
- Shall determine the energy of release required to evolve each of the volatile compounds
  - Will drive future large scale processing techniques
- Shall heat the samples in a step-wise manner with dwell periods
  - Allowing the samples to periodically come to steady state will minimize the effects of release dynamics on the energy of release curves
  - Evaluate impact on design mass and complexity for minimizing temperature gradients during heating (<25 K) which may skew volatile energy release curve characterization
- Shall capture evolved hydrogen and water
  - If water is present, capture 0.25 to 2 ml of water total (3 operations); water will be separated, condensed, and visually verified

RESOLVE Requirements

Understanding the Resource – Regolith & Environment

- Shall characterize lunar regolith particle size, shape, and color, and image frost/ice (if present) by optical microscopy

- Shall identify and distinguish the presence and form hydrogen (hydrate, water ice/frost, solar wind hydrogen, NH_3, CH_4, etc.) in lunar regolith

- Shall characterize the chemical composition of lunar surface regolith (components detectable to ~1 wt%).

- Shall measure the geo-technical characteristics of the regolith to provide engineering data for follow-on resource excavation unit including (but not limited to): shear-strength, compaction/density, cohesiveness, and 'crushability'

- Shall measure the lunar regolith temperature to an accuracy of 1 K at the surface and to a depth of 10 cm.

RESOLVE Requirements
In-Situ Resource Utilization (ISRU) Operation

- Water/volatile processing
  - If water is present, capture 0.25 to 2 ml of water total (3 operations)
  - Water will be separated, condensed, and visually verified
  - Water will be electrolyzed after capture

- Oxygen production from regolith
  - Produce minimum of 5 grams of oxygen with 80 watts power maximum per production cycle
  - Perform a minimum of 2 production cycles to validate sealing and feedstock/spent regolith transfer; 5 production cycles nominal
  - Mass <10 kg; Volume < 15 liters
  - Minimize heat loss and production cycle time
  - Design a demonstration package with plans for how the process can be scaled up