In-Situ Resource Utilization (ISRU) Capabilities & Roadmapping Activities

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New Space Exploration Vision

- **On January 14, the President announced a new vision for NASA**
  - Implement a ***sustained*** and ***affordable*** human and robotic program to explore the solar system and beyond;
  - Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
  - Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
  - Promote international and ***commercial participation*** in exploration to further U.S. scientific, security, and economic interests.

"This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart." – President Bush

NASA Capability Roadmaps

- **President's Commision on Implementation of U.S. Space Exploration Policy (Aldridge Committee)**
  - Established on January 24th, 2005 and final report released June 2004
  - Recommendation 4-1, "The Commission recommends that NASA immediately form special project teams for each enabling technology" (17 identified)
- **In October, 2004, NASA initiated 15 Capability Roadmap teams with the following key process elements:**
  - Based on Presidential Commission recommendations and prior knowledge of mission and program needs
  - Develop common formats, guidelines, constraints
  - Broad roadmap categories should be defined to encompass key technical areas
  - Technical input derived from existing material, CRAI reports, etc. to maximum extent possible
  - Teams led by technical experts (1 NASA/JPL, 1 non-NASA)
  - Guidelines for team membership (1/3 NASA/JPL, 1/3 industry, 1/3 academia)
  - Key center representatives participate and provide technical input and support
  - Foundation for FY07 budget planning and decisions
  - National Academy reviews

Key Architecture & Strategic Decisions For ISRU

ISRU: In-Situ Resource Utilization

Key Strategic Decisions	Date Decision is Needed	Impact of Decision on Capability
When will ISRU be used on human missions and to what extent?	2005 to 2012 Early Robotic Exploration	Determines need for 'prospector' and demonstration missions. Determines location and transportation architecture.
To what degree will Mars requirements drive Lunar design selections, i.e. propellants	2005 to 2008	Determines if Lunar landers utilize the same or different propulsion elements.
Level of reusability: single-use vs multiple-use elements	2010 to 2012	Determines whether one or two landers will be developed for Lunar operations
Level of commercial involvement	2005 for 2010 Early Robotic Exploration	Determines long term NASA funding needs. Early involvement required max. benefit
Is long-term human presence on the Moon a goal?	2010 to 2015	Determines scope of Lunar ISRU, and what technologies and environments are relevant
Is water readily available on the Moon for propellants and life support?	2010 to 2012	Determines long term sites for Lunar bases and transportation architecture
Is water readily available on Mars for propellants and life support?	2010 to 2015	Determines sites for human Mars exploration and extent of ISRU use on Mars.

Key Architecture Decisions	Date Decision is Needed	Impact of Decision on Capability
Single Base w/ forays vs Multiple individual missions	2008 to 2012	Determines surface lander and habitat designs, and when and to what extent Lunar ISRU is incorporated
Pre-Deploy vs All-in-one Mission	2008 to 2012 for Lunar and 2015 to 2020 for Mars	Determines size of lander/habitat and level of ISRU incorporation
Direct Return, Low Orbit Rendezvous, or L1/High Orbit Rendezvous	2008 to 2012 for Lunar and 2015 to 2020 for Mars	Determines impact of ISRU propellant production on mission & architecture mass and cost.
Surface Power-Solar vs Nuclear	2009-2010 for Lunar base, 2015-2020 for Mars base	Determines size, operating duration, and cycle of ISRU plants
Abort-to-Surface or Abort-to-Orbit	2008 to 2012 for Lunar and 2015 to 2020 for Mars	Determines if use of ISRU propellant for ascent propulsion is acceptable

ESAS Surface Study

- **In May, 2005, the new NASA Administrator initiated the Exploration System Architecture Study (ESAS) or "60 Day Study"**

- **Notional Lunar Architecture for Surface Study**
  - 2018 Return to the Moon (RTM)
  - 4-7 day "sortie-class" missions in 2018-2020
    - 2 missions per year (2018, 2019)
    - One additional sortie mission interspersed within base deployment phase
    - Global access
    - 4 crew per mission
    - Extensive EVA (all 4 crew [2 x 2 teams], each day on surface)
    - Local mobility (unpressurized rovers)
    - Mix of exploration technology and science experiments
  - Permanent base deployment missions 2020-2022
    - Robotic delivery and deployment
    - (predeployment of backup ascent vehicle prior to first crew arrival)
  - Steady-state base operations 2022-(2030)
    - 4 lunar landings per year:
      - 6 month crew rotations
      - Logistics mission interspersed between crew flights
    - Extended mobility (pressurized rovers)
    - Emphasis on in-situ resource utilization

Objectives of Lunar ISRU Development & Use

ISRU: In-Situ Resource Utilization

- Identify and characterize resources on Moon, especially polar region
- Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human Mars missions
  - Excavation and material handling & transport
  - Volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems for oxygen and fuel production
  - Cryogenic fluid storage & transfer
- 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 human space transportation and presence on Moon
  - Lower Earth-to-Orbit launch needs
  - Enables reuse of transportation assets and single stage lander/ascent vehicles
  - ➢ Lower cost to government thru government-commercial space commercialization initiatives

Objectives of Mars ISRU Development & Use

ISRU: In-Situ Resource Utilization

- Utilize Earth-based, ISS, and Lunar ISRU development, testing, and experience to maximum extent possible
- Identify and characterize resources on Mars, especially water
  – Utilize information from past, current, and planned Science missions to provide critical environment, resource, and design data when possible
- Develop and evolve Mars ISRU capabilities that reduce cost, mass, and risk of human exploration and *enable* exploration capabilities as early as possible
  – ex. Surface mobility & hoppers, power-rich distributed systems, enhanced radiation shielding, manufacturing/construction, plant growth/food production, etc.
- Perform ISRU demonstrations in step-wise approach to increase confidence in environment/resource understanding and reduce mission application uncertainties
  - **Lessons learned from a mission can only influence design of hardware for missions 2 or 3 opportunities (4 or 6 years) later due to hardware development time, trip times, and extended surface operations to collect data**
  – Parallel investigations of atmospheric and regolith/water-based processing with convergence before human mission
- Permanent Human presence in space and human missions beyond Mars (gateway to asteroid belt?)
  – ISRU on Phobos/Deimos; Mars-Sun L1 depot; ….
  – Space exploration is “a journey, not a race”

Lunar ISRU Mission Approach

ISRU: In-Situ Resource Utilization

Four Phases

- **Robotic Phase**: Robotic precursors to identify resources and validate critical processes
  - Lunar Reconnaisance Orbiter (2008)
  - Lunar Robotic Exploration Program (RLEP) Mission 2 lander to poles (2010+)
  - RLEP Mission 3?
- **Sortie Phase**: Early human missions (4 to 14 days) to check out systems and operations until long-term Outpost initiated
  - Demonstrate critical ISRU capabilities at sub-Outpost scale production rates (excavation, oxygen production, water/hydrogen extraction, liquid oxygen storage & transfer)
- **Outpost Pre-deploy Phase**: Pre-deploy ISRU assets to be ready at start of crew occupation of Outpost
  - Surface regolith excavation and manipulation
    - Excavation for volatile extraction and regolith processing
    - Berms and shielding for radiation and plume protection
    - Site/landing pad preparation and road/dust mitigation
  - Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O)
  - Oxygen (O_2) production from regolith processing
  - Production/regeneration of fuel cell reagents
  - Cryogenic storage & transfer

Lunar ISRU Mission Approach

ISRU: In-Situ Resource Utilization

- **Outpost Phase**: Develop infrastructure at one base for Mars mission 'dress rehearsals' and sustained human presence in space
  - Initial Phase ISRU Capabilities:
    - Pilot regolith excavation and oxygen production, storage, & transfer capability sized to support refueling 2 ascent vehicles per year (~3500 kg/vehicle) and habitat & EVA life support needs for 4 crew per year (~3000 kg)
    - Hydrogen production as fuel dependant on results of RLEP and Sortie missions to lunar poles
    - ISRU produced oxygen ready for 2^{nd} Outpost crew return vehicle
  - Mid-Term ISRU Capabilities
    - In-situ fabrication and repair
    - In-situ power generation
    - Thermal energy storage & use
    - Increased oxygen/fuel production to enable completely reusable landers or surface hoppers
  - Long-Term Lunar Capabilities
    - In-situ manufacturing of complex parts and equipment
    - Habitat and infrastructure construction (surface & subsurface)
    - In-situ life support – bio support (soil, fertilizers, etc.)
    - Helium-3 isotope (^3He) mining
- **Outcome of ISRU capability for Outpost**
  - Enables cost effective lunar surface operations.
  - Enables surface hopping to other locations for short term science mission objectives

Lunar ISRU Conductivity to Mars

ISRU: In-Situ Resource Utilization

- **Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human 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 surface exploration assets linked to ISRU capabilities that enable new exploration capabilities**
  - Human and robotic hoppers for long-range surface mobility and global science access; power-rich distributed systems; enhanced radiation shielding, etc.
  - Repair, fabrication, and assembly techniques to mitigate mission risk and logistics mass.

ISRU Site Selection (in priority)

- ISRU site selection and ranking based on combination of resource available and ease of ISRU processes required to excavate resources and extract usable products.

	ISRU Site/Resource	*Rationale*
1	South Lunar Pole: Hydrogen, environment	Presence of hydrogen, water, and/or other hydrogen-baring molecules (NH_3, CH_4, etc.) could minimize need for oxygen extraction from regolith and enable in-situ hydrogen or hydrocarbon fuel production. Resource extraction through simple regolith heating, but does require excavation capabilities at 40K. Environmental factor of almost permanent sunlight and shadow could help ISRU and propellant storage processes and minimize need for start-up/shutdown operations associated with equatorial sites.
2.	Aristarchus plateau: Pyroclastic glass, solar wind volatiles, in-situ solar power production	Similar rational to High Titanium ores. Pyroclastic glass may also be easier to excavate and transfer.
3	NW-W Tranquililatis: High Titanium (iron), solar wind volatiles, in-situ solar power production	Oxygen extraction from high titanium ores utilizes lowest energy process. New work in fused salt electrolysis raises oxygen extraction percentage compared to hydrogen reduction. High titanium ores also contain highest concentrations of deposited solar wind volatiles.
4	North Lunar Pole: Hydrogen, environment	Similar rationale to South Lunar Pole. Compare and contrast hydrogen bearing areas between poles to determine best terrain, resource concentration, and regolith properties for final Outpost site selection
5	Near-equatorial highlands: Iron-poor, aluminum rich highlands	Possible interest in aluminum, calcium, and silicon extraction for long-term fabrication and construction of power and habitat infrastructure
6	Mare Crisium: High iron, low titanium regolith	Oxygen extraction from iron oxide.

ISRU Sortie Demonstrations (in priority)

ISRU: In-Situ Resource Utilization

	ISRU Demonstration	*Rationale*
1	Regolith excavation & manipulation capabilities (regolith beneficiation, berms & trenching, etc.)	Required for all lunar ISRU processing and construction, Mars water extraction and mineral processing, protection from plume debris, and possibly nuclear reactor deployment
2*	Demonstration of oxygen extraction from regolith and oxygen separation, liquefaction and storage during lunar daytime	Required for sustained lunar presence and cis-Lunar transportation. Cryogenic storage and transfer also supports surface fuel cell power infrastructure
3**	Integrated excavation & volatile extraction & collection	It is known that lunar volatiles are lost due to simple agitation of regolith, however the amount of loss is unknown. To understand and minimize losses, regolith excavation & volatile extraction must be integrated (unlike oxygen or metal extraction). This capability could also be applicable to large scale hydrogen/water extraction (#6), and for water extraction from Mars regolith
4	Surface construction techniques (pads, roads, beams, plates, etc.)	Reduces dust problem around habitat for Outpost operations and provides lessons learned for possible construction at Outpost
5	Metal/silicon extraction (may be tied to oxygen extraction demonstration)	Possible feedstock for in-situ manufacturing, construction, and energy infrastructure growth
6	Larger scale hydrogen/water/volatile extraction at poles (if Sortie flown to lunar pole)	Build off of lessons learned from RLEP mission before full Outpost operations begin
7	Solar energy/power generation and storage infrastructure growth	Provides knowledge for possible use at Outpost
8	In-situ manufacturing & repair demonstration (internal and/or external)	Supports spare part manufacturing and repair at Outpost. For internal processes, enables reduced gravity testing validation of Earth-based development activities

Note 1: Assumes RLEP missions to lunar pole(s) to characterize polar volatiles, regolith, and environment are flown before human Sortie missions

*Note 2: Until Earth-based technology development is performed, downselection of a single oxygen extraction process is not possible. Also, if in-situ oxygen production is critical to long-term lunar surface sustainability, primary and backup processes should be pursued. Therefore, more than on oxygen extraction process demonstration may be necessary. Common packaging and support equipment would be utilized to minimize the cost of flying a 2nd demonstration.

**Note 3: The need to extract and collect solar wind volatiles is dependant on (i) determining hydrogen/water availability at the poles, (ii) Outpost site selected, and (iii) desire for other solar wind volatiles (i.e. helium 3)

Note 4: Demonstrations 1, 2, 3, 6, & 7 should be designed to continue operation for as long as possible after crew departs

ISRU Sortie Operation Sequence

- Day 1
  - Crew deploys & activates ISRU demonstration; Ground personnel verify communication pathway and that demo is operational.
  - Crew provides regolith feedstock to ISRU demonstration if separate regolith excavation and delivery unit/demonstration is not manifested
  - Crew collects sample (TBD kg) of regolith feedstock to ISRU demo for return to Earth
  - If combo rover for excavation and crew mobility is used, set up autonomous excavation and delivery capability after initial EVA
- Day 2 or 3
  - Crew observe operation and performance of ISRU demonstration
  - For excavation or trenching demonstrations, crew can utilize opportunity for science objectives
- Day X; Contingency
  - Troubleshoot/repair demonstration if failure in process or operation occurs
- Last Surface Stay Day:
  - If ISRU regolith processing demonstration (oxygen, metals, construction materials, etc.), than have Crew collect sample of product for Return to Earth
  - If ISRU construction demonstration, have Crew perform measurements and/or tests to verify construction characteristics
  - Crew verifies ISRU demonstration is set for continued operation after departure or disassembles and stows (TBD) hardware to return to Earth if ISRU demonstration failed during operation

Note: At this time, there is minimal additional benefit expected from ISRU demonstrations if mission surface stay is extended from 4 to 7 Earth days (further evaluation of construction demonstrations required). This is because:

a) Fundamental feasibility of process efficiency and operation will be demonstrated in first day of operation
b) Product variation from day 4 to 7 due to subtle environment or trace constituent presence will be undetectable
c) Determination of ISRU process reliability and maintenance characteristics will require months of operation (this leads to desire for ISRU demonstrations to continue to operate after crew departs)

ISRU Activities During Outpost Pre-deploy

ISRU: In-Situ Resource Utilization

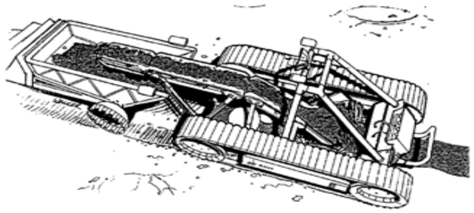
- Pre-deployment of some ISRU elements is advised to:
  - Support site preparation for 1st human mission
  - Complete production of initial ISRU products (such as oxygen or propellants) before 1st human crew arrives to eliminate risk to mission success and increase confidence in ISRU.

	*ISRU Element**	*Purpose & Characteristics*
1	Regolith excavation and transportation (excavator & hauler)	– Common mobile platform utilized for excavator, hauler, & surface construction capabilities – If nuclear reactor needs to be deployed from lander, regolith excavator should be incorporated into same mission to: tow reactor to placement site, excavate to bury, and/or build shield berm around reactor before activation.
2	Oxygen production from Regolith (pilot scale)	– 8 to 60 MT of oxygen per year (depends on mission use assumed) – Trade required on lander mounted vs deployed unit after landing. – Incorporate unit on modified lander for connection to cryogenic fluid storage and distribution
3	Long-term cryogenic fluid storage and transfer of oxygen and fuel	– Modify lander to incorporate active cooling to oxygen & methane propellant tanks and add disconnects and pumps for initial storage & transfer capabilities – **Examine ability to use Descent lander tank or scavenge tanks or tank packages from other non-reusable landers for infrastructure growth** (note: MLI insulation on cryo tanks is easily damaged)
4	Lunar polar hydrogen/water excavation and extraction (assumes lunar polar Outpost location)	– Combines excavation and hydrogen/water extraction into one integrated unit to minimize losses during processing – Assumes RLEP precursor mission determined resource constituents, concentrations, and regolith properties – Extraction rate and type of power system depends on amount of time spent in permanently shadowed crater
5	Surface construction (pads, berms, roads, etc.)	– Reduces risks associated with returning to same location – Possibly uses common platform and devices with excavator & hauler

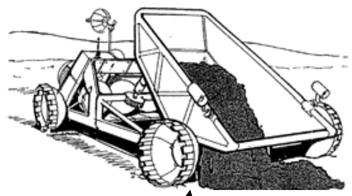
*Note 1: ISRU Element delivered is at pilot rate production capabilities as a minimum

Lunar Oxygen Production Elements

Regolith Excavation



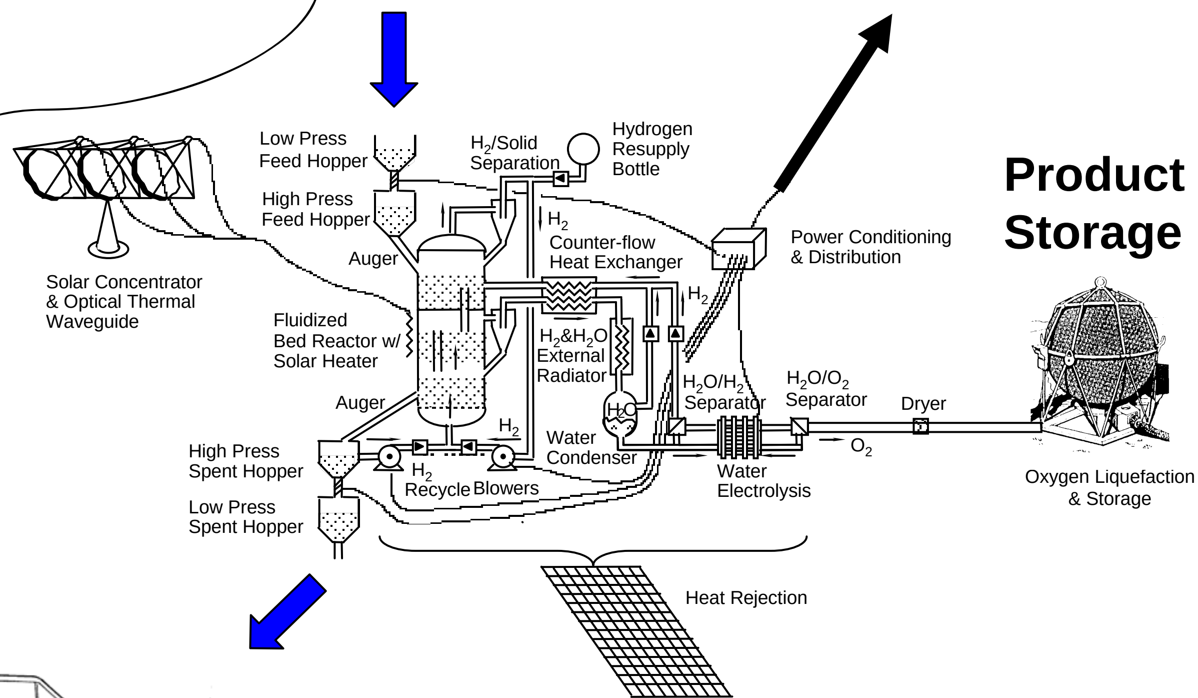
Regolith Transport

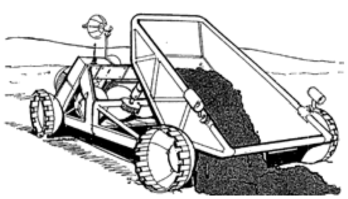


Power Source

(Solar Array or Nuclear Reactor)

Product Storage





Regolith Processing

Note: Hydrogen reduction of regolith shown as example. Other options being considered include (a) carbo-thermal reduction, (b) salt or molten silicate electrolysis, and (c) acid reduction

ISRU Outpost Pre-deploy Recommendations

- LSAM & Cargo Lander (Sortie & Outpost Lunar Missions) – Descent Stage
  - Propellant tanks for the descent stage should have one or more of the following modifications:
    a. Ability to store and transfer residual oxygen (and fuel) for surface EVA and fuel cell power needs to extend surface mobility and EVA duration
       - Extra valves, pumps, and EVA disconnects required

    b. Ability to receive and liquefy lunar produced oxygen/fuel from ISRU pilot plant as low cost/mass cryo storage depot.
       - Extra cryocoolers and valving required

    c. Ability to remove descent stage tanks to create surface cryo depot 'tank farm'.
       - Extra disconnects required
  - The challenges are scaring the vehicle with couplings and interfaces to allow functions while minimizing extra mass and complexity (especially for c)

- LSAM (Outpost Lunar Mission) – Ascent Stage
  - Disconnects, valves, and manifolds to allow ascent tanks to be filled from oxygen (fuel) storage and transfer Logistics carrier

ISRU Activities During Lunar Outpost (2022+)

ISRU: In-Situ Resource Utilization

- Deployment of some ISRU elements during the first and subsequent missions to Outpost is advised to:
  - Introduce mission supporting ISRU on an as-needed basis
  - Increase capabilities of pre-deployed ISRU with growth in Outpost goals and objectives

	*ISRU Element**	*Purpose & Characteristics*
1	In-situ manufacturing & repair	– 'Machine shop' to fabricate spare parts, especially for high-wear items for excavation and regolith processing – Additive, subtractive, and formative techniques for multiple materials (metals, plastics, and ceramics) – Initially utilizes feedstock from Earth – Repair techniques for both internal and external hardware based on past studies of failures and mission contingencies
2**	Metal/silicon extraction (if separate or addition to oxygen production process)	– Supports long-term in-situ manufacturing & repair – Process utilized may be add on to existing Oxygen production process pre-deployed or may utilize new process for specific elements of interest
3**	In-situ energy production & distribution growth	– Energy Production: solar arrays, solar thermal, …. – Energy Transfer: wires, power beaming, …. – Energy Storage: Fuel cell reactants, thermal heat sinks, ….
4	Internal waste recycling	– Supports long-term in-situ manufacturing & repair by providing alternative source for feedstock – May be source of carbon for lunar processing
5	Surface construction habitat and infrastructure growth	– Includes construction of non-pressurized and pressurized structures, space observatory elements, etc.

*Note 1: ISRU Element delivered is at pilot rate production capabilities as a minimum

**Note 2: Priority denoted assumes precursor demonstrations were flown during the human Lunar Sortie phase. If a precursor demonstration was not flown, then precursors of these elements would be flown before pilot rate production capabilities are established

Forward Work

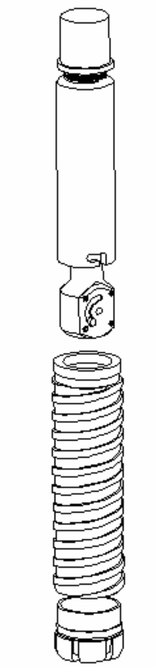
- Perform studies and trades to determine requirements and specifications for Sortie and Outpost scale ISRU processes
  - Example: numbers & types of excavation vehicle; separate versus integrated excavation & hauling
- Initiate ISRU technology development plan to meet objectives and schedule of human lunar exploration program
- Examine “Incremental Build” vs “Outpost Pre-Deploy” approach on ISRU capability and element design and deployment
  - Continue to work with mission planners on when ISRU is utilized and transition to reusable landers & hoppers
- Support Robotic Lunar Robotic Exploration Program
  - 2nd RLEP Mission to Lunar Pole for “ground truth” of hydrogen source
  - Possible follow-on RLEP missions
- Examine space commercialization potential of ISRU
  - Centennial Challenges
  - Commercial payloads on RLEP missions?
  - Partnerships with commercial enterprises

Regolith and Environment Science & Oxygen and Lunar Volatiles Extraction (RESOLVE) Overview

ISRU: In-Situ Resource Utilization

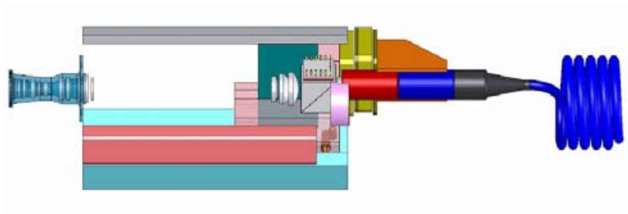
- RESOLVE project will develop and fabricate a **prototype device** that will excavate lunar regolith from permanently shadowed craters, determine the quantity and form of hydrogen in and the physical/mineralogical characteristics of the regolith, and demonstrate ISRU.

- Project initiated through ESMD ICP last June under the Technology Maturation Program (official project start 2/1/05)



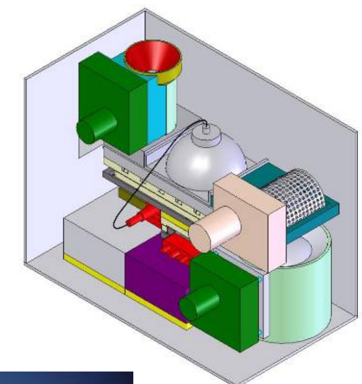
The five RESOLVE modules are:

- **EBRC - Excavation and Bulk Regolith Characterization (KSC/CSM/NORCAT)**
  Provide capability of extracting samples of regolith from the lunar surface and determine bulk characteristics of the regolith.



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

- **ERPC - Environment and Regolith Physical Characterization (JPL)**
  Determine the fine-grain 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.

- **LWRD – Lunar Water 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 Target Design

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

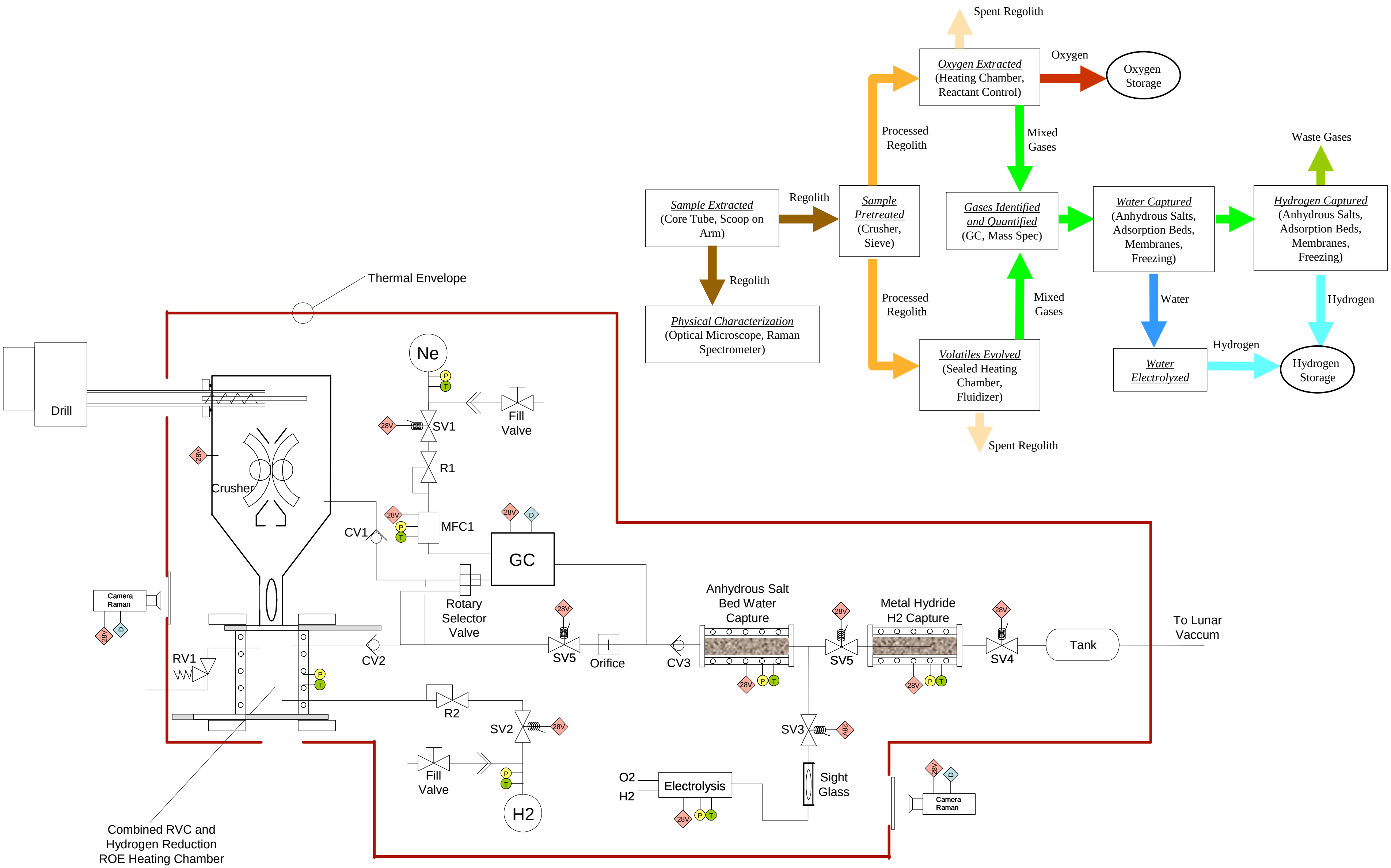
RESOLVE Objectives

ISRU: In-Situ Resource Utilization

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 & 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 Integrated Schematic & Flow Diagram

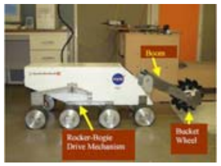
ISRU: In-Situ Resource Utilization

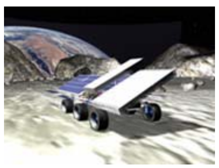


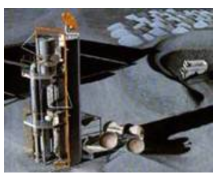
Backup

Past & Current Lunar ISRU Activities

ISRU: In-Situ Resource Utilization







ISRU Technology Development

- Lunar ISRU has a 30 year history of laboratory testing of lunar solar wind volatile measurement and oxygen extraction from simulants and Apollo samples
- Hydrogen reduction of Ilmenite fluidized bed (Carbotek)
- KC-135 lunar excavation force testing (Texas A&M)
- Bucket wheel excavator (CSM, NORCAT)
- Solar concentrator for ISRU furnace (PSI)
- In-situ solar cell/array fabrication (Univ of Houston)
- Lunar brick fabrication and characterization
- Lunar concrete (wet and dry) characterization
- Carbo-thermal reduction of regolith (Aerojet, SBIR)

ISRU Subsystem & System Development & Ground Testing

- Hydrogen reduction of Ilmenite fluidized bed (Carbotek)
- Carbo-thermal reduction of regolith (Aerojet, SBIR)
- Recent ICP/BAA's
  - RESOLVE: lunar polar resource characterization and oxygen extraction from regolith (JSC)
  - PILOT: Excavation, lunar oxygen extraction, & oxygen storage (LMA)
  - Ilmenox: Fused-salt electrolysis of lunar iron oxide and silicates (British Titanium)

Flight Hardware & Demonstrations

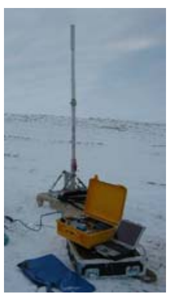
- Apollo: regolith scooping, coring, and grinding and analysis of rock samples on the Moon
- Clementine & Lunar Prospector
- Lunar Reconnaissance Orbiter in 2008
- Potential for RESOLVE type mission in 2010.

Past & Current Mars ISRU Activities

ISRU: In-Situ Resource Utilization

ISRU Technology Development

- Mars atmosphere adsorption pump collection (JPL, ARC, LMA, JSC, PNNL)
- Mars atmosphere solidification pump collection (LMA, SBIR)
- Zirconia CO_2 Electrolysis (Univ. of Arizona, Allied Signal, Old Dominion, SBIR)
- Water Electrolysis/Decomposition (JSC, LMA, SBIR)
- Reverse Water Gas Shift (SBIRs, KSC)
- Methane reformer (JPL, SBIR)
- Hydrocarbon fuel development (SBIR, JSC)
- Microchannel Chemical/Thermal System Technology for ISRU (PNNL, SBIR)
- Surface cryogenic liquefaction and storage (JSC, NIST, SBIRs, LMA)



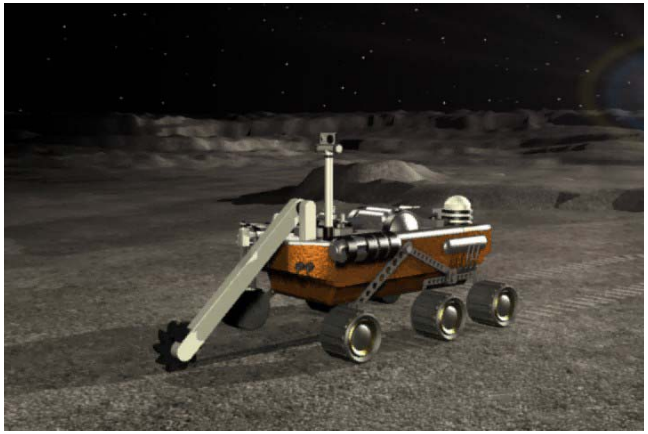
ISRU Subsystem & System Development & Ground Testing

- CO_2 collection and storage subsystems tested
- 1st Generation Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing
- 1st Generation Reverse Water Gas Shift with and w/o Fuel production
- 2nd Gen SWE system breadboard - designed and subsystems built
  - Testing for Battelle BAA this FY
- Mars deep drilling CDDF

Flight Hardware & Demonstrations

- Mars ISPP Precursor (MIP) flight demo manifested on 2001Mars Surveyor Lander
  - Flight hardware certified and placed in Bonded Storage at JSC
- Mars regolith excavation (Viking, Phoenix)

Lunar Polar Volatile Extraction Demonstration (RLEP)



Summary Data
Mass = 300 kg
Power=100 to 200 W (self provided)
Volume = 1 to 2 m^3

Operational Capability

The Lunar Polar Volatile Extraction Demonstration (LPVED) will excavate and process 20 kg of polar regolith per hour to extract volatiles that may be found in the permanently shadowed craters. Volatiles of interest for capture and storage include: hydrogen, water, ammonia, and hydrocarbons such as methane. The LPVED must operate autonomously at 40 K temperatures for a minimum of 10 hrs, and return to the sunlit landing site to return captured resources to the lander. Excavation down to 0.5 m minimum.

System Functionality

To operate in permanently shadowed craters, the LPVED must be semi-autonomous with communication capability with Earth & crew via satellite. The LPVED must provide autonomous route planning and resource detection capabilities. Once concentrations above desired levels are detected, LPVED must plan and execute regolith excavation and processing procedures. Once per day or if capture tanks are filled, the LPVED must return to the lander for offload and possible power regeneration if fuel cells are used.

Reference Concept

The LPVED is a combination prospector and feasibility demonstrator for lunar polar volatile resource collection. It will consist of five major elements, the mobile rover base, regolith excavation & feed system unit, regolith volatile chamber, volatile separation and storage unit, and energy generation & distribution unit.

Mobile rover. Mars Exploration Rover (MER) size vehicle (200 kg). The rover will include autonomous navigation, communication, and command and control functions. A neutron spectrometer for hydrogen location detection is also included.

Regolith excavation & feed system unit. Consists of excavator (bucket wheel shown), auger, and crusher to move regolith from the entry port into the regolith processing unit with minimal loss of trapped volatiles. A drill might also be incorporated for resource mapping.

Regolith Volatile Chamber. Will thermally process the regolith to extract all volatiles.

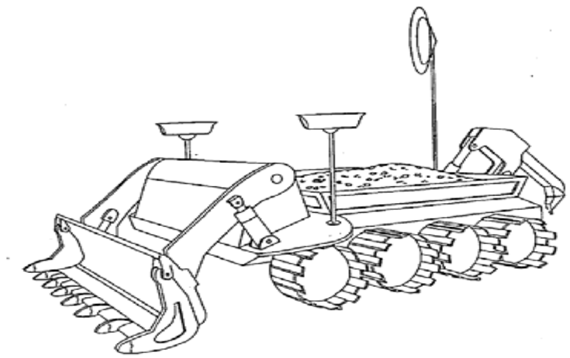
Volatile separation, liquefaction, and storage unit. Will identify and measure all volatiles released. It will capture hydrogen and water separately in series. Simple collection concepts (adsorption) or use of low external temperature environment will be utilized

Energy generation and distribution unit. Will include either dynamic radio-isotope power generation or fuel cell power generation for both thermal and electrical power to the LPVED and rover.

*Source

Estimates based on MER/MSL size and payload capability and early estimates from Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE) project

Lunar Excavation Demo (Sortie)



Summary Data
Mass = 300 to 400 kg
Power=100 - 200 W (self provided)
Volume = 2 to 3 m^3
Excavation Rate = 2-3 kg/hr

Operational Capability

The Lunar Excavator is designed to evaluate techniques for regolith excavation and manipulation required to support both regolith processing and surface construction operations. The excavator will be a semi-autonomous and tracked or multi-wheeled to provide maximum traction and excavation force. Power is provided by rechargeable batteries or a fuel cells. The excavator may incorporate a bucket and/or back-hoe type device to also evaluate techniques such as berm construction. The lunar excavator will be designed to operate during lunar day and survive lunar night conditions. Excavation capability down to 1 m and berm height creation of up to 3 m minimum.

System Functionality

The Lunar Excavator will operate during lunar day conditions. It will operate semi-autonomously with ground and crew interaction and redirection possible. The Lunar excavator must provide autonomous route planning and must plan and execute regolith excavation and surface construction procedures based on pre-defined operating modes.

Reference Concept

The Lunar Excavator demonstration is a precursor to excavation needs for pilot and full-scale oxygen production. The Lunar excavator will consist of three major elements, the mobile base unit, the excavation unit, and mobile power unit.

Mobile base unit. Mars Exploration Rover (MER) size vehicle (200 kg) to Mars Science Laboratory (MSL) size vehicle (600 kg). The mobile base unit will include autonomous navigation, communication, and command and control functions. It is envisioned that this unit will be a precursor to a common platform for both excavation and regolith hauling. Further commonality with crew transportation is also envisioned

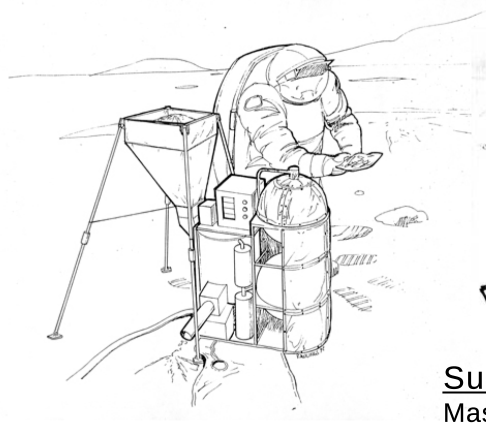
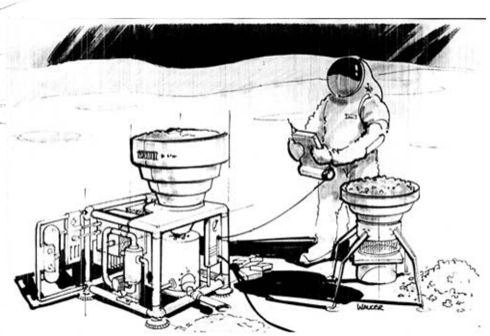
Excavation unit. Standardized attachment locations at the front and back of the mobile base unit will allow incorporation of different excavation concepts: bucket, and bucket wheel excavation are the two primary methods for excavation for regolith processing, bucket and back-hoe type devices for construction, and blades and box scrappers for road and landing pad construction.

Mobile power unit. The Lunar Excavator will incorporate a standardized mobile power unit; either rechargeable batteries or fuel cells depending on total duration and power levels required.

Source

Estimates based on MER/MSL size and payload capability and early estimates from Colorado School of Mines during RASC study

Lunar Chemical Processing & Storage Demo (Sortie)

Summary Data
Mass = 226 kg
Power=~1-3.5 kW
Volume = 1 m^3
Production rate = 0.2-0.3 kg/day
Duration = 14 days min.

Operational Capability

The Lunar Chemical Processing & Storage Demonstration (LCPSD) will produce, liquefy, and store 1 kg of oxygen per hour. A minimum of 100 kg of oxygen will be produced and stored. Regolith delivery to the LOPSD will be provided via astronaut or separate regolith excavator/transport unit. The LOPSD will operate autonomously, however crew involvement may be required for regolith delivery and if a failure during operation occurs.

System Functionality

The LCPSD will provide all of the functions for self-sufficient operation, except for regolith delivery. Functionality required include the ability to pre-condition and deliver regolith to an oxygen extraction processing chamber, separate and store evolved oxygen, generate and distribute solar and electrical power for all operations, and remove processed regolith before entry of new pre-conditioned regolith.

Reference Concept

The LCPSD is a precursor to the Lunar Oxygen Pilot Plant. Different versions may be flown depending on the number of concepts to be demonstrated before final selection. It will consist of four major elements, the regolith inlet/outlet feed system unit, regolith processing unit, energy generation and distribution unit, and volatile separation, liquefaction, and storage unit.

Regolith inlet/outlet feed system unit. Consists of pressurized hoppers, augers, and crushers to move regolith from the entry port into the regolith processing unit with minimal loss of trapped volatiles. Also removes processed regolith without loss of oxygen produced.

Regolith processing unit. Will process the regolith to extract oxygen. Processes of interest include:
- Carbothermal reduction,
- Electrolysis (molten & fused-salt), and
- Acid reduction (sulfuric and hydrofluoric).

These techniques can processes a larger range of regolith besides just ilmenite, and can be used as a starting point for metal and silicon extraction from lunar regolith.

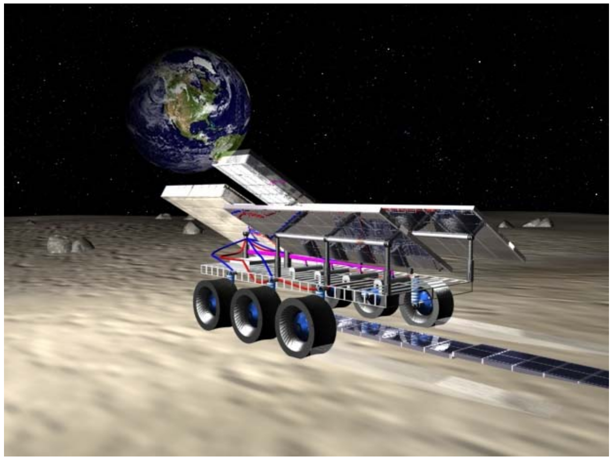
Energy generation and distribution unit. Will include solar concentrators and hardware to provide both thermal and electrical power to the Lunar oxygen production demonstration so that the unit is self-sufficient except for regolith delivery.

Volatile separation, liquefaction, and storage unit. Will store all the oxygen produced from the processing chamber for possible use during the mission. Depending on the location of the LOPSD and amount of oxygen produced, specially modified lander propulsion system oxygen tanks may be used after landing. Other concepts, such as inflatable tanks with active cooling, may also be demonstrated.

Source

90 Day Study and Data based on analysis provided in, Eagle Engineering Report 175, July 7, 1988.

Solar Array Production Demonstration (Sortie)



Summary Data
Mass = 100 kg
Power= 50 to 100 W (self provided)
Volume = 0.4 m x 0.6 m x 1.2 m

Operational Capability

The Solar Array Production Demonstration (SAPD) will demonstrate fabrication of silicon solar cells into discrete arrays on the lunar surface. Arrays fabricated will incorporate 10 cm x 10 cm cells with 15 cells in series and fabricated on 20 cm wide melted regolth substrate to produce 12 volts and 5 amps of power.

System Functionality

The SAPD will include solar collectors to melt the regolith substrate and for vacuum deposition of cell constituents and solar thermal electrical power generation. The solar collector combined with a solar thermal electrical generator will provide electrical power needs for rover and solar cell/array production hardware. Batteries and/or thermal heat sink material will be used for lunar night survival.

Reference Concept

The Solar Array Production Demonstration (SAPD) is a small proof of concept demonstration of in-situ energy production. Some solar cell production consumables, such as silicon and dopents will be provided from Earth. Separate ISRU processes will be developed to extract these consumables from lunar regolith. The LPVED will consist of four major elements, the mobile rover base, solar collector unit, cell/array deposition unit, and solar electrical and thermal energy production and storage unit.

Mobile rover. The rover is a simple, slow moving device with limited articulation requirements. The rover must perform some leveling and path clearing capabilities for solar array production. Due to the slow speed array production path planning can be supported or led by the ground.

Solar collector unit. Consists of multiple solar collectors to and fiber optic cables to concentrate and direct solar energy for four main tasks: regolith melting/sintering, cell/array production, conversion to electrical energy, conversion to thermal energy for immediate and lunar night survival.

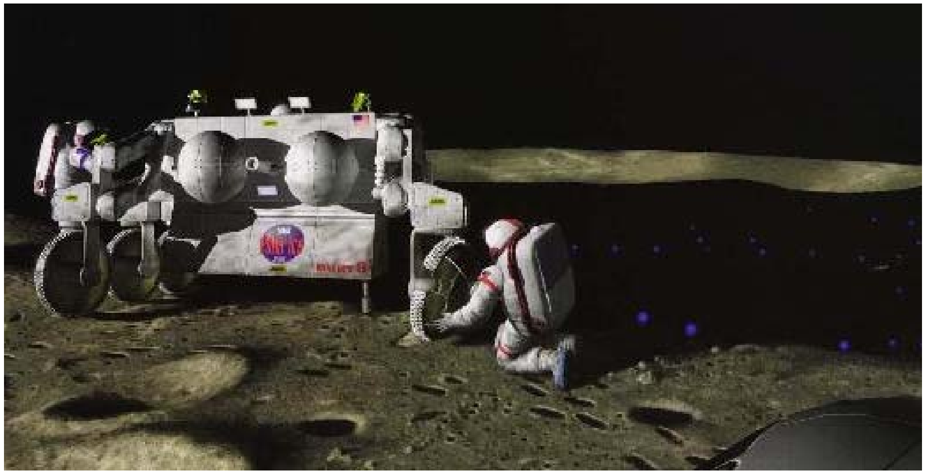
Solar cell/array production unit.. Includes several vapor deposition devices that operate in sequence to produce solar cells which are then connected in parallel and series to produce the desired array power characteristics.

Solar energy production and storage unit. Consists of thermal to electrical energy conversion hardware, batteries for electrical energy storage, and heat sinks/phase change materials for thermal storage.

Source

University of Houston, Dr. Alex Ignatiev

Lunar Polar Resource Extractor (Outpost)



Summary Data
Mass = 1200 kg
Power= 15 KW (self provided)
Volume = 1.5 m^3

Operational Capability

The Lunar Polar Resource Extractor (LPRE)will excavate and process 50 kg of polar regolith per hour to extract volatiles that may be found in the permanently shadowed craters. Volatiles of interest for capture and storage include: hydrogen, water, ammonia, and hydrocarbons such as methane. The LPRE must operate autonomously at 40 K temperatures for a minimum of 12hrs, and return to the sunlit landing site to return captured resources to the lander. Excavation down to 1 m minimum.

System Functionality

To operate in permanently shadowed craters, the LPRE must be semi-autonomous with communication capability with Earth & crew via satellite or communication relay at the crater rim. The LPRE must provide autonomous route planning and resource detection capabilities. Once concentrations above desired levels are detected, LPRE must plan and execute regolith excavation and processing procedures. Once per day or if capture tanks are filled, the LPRE must return to the Outpost for offload and possible power regeneration if fuel cells are used.

Reference Concept

The LPRE is a combination prospector and lunar polar volatile resource collector. It will consist of five major elements, the mobile rover base, regolith excavation & feed system unit, regolith volatile chamber, volatile separation and storage unit, and energy generation & distribution unit.

Mobile rover. The rover will include autonomous navigation, communication, and command and control functions. A neutron spectrometer for hydrogen location detection is also included.

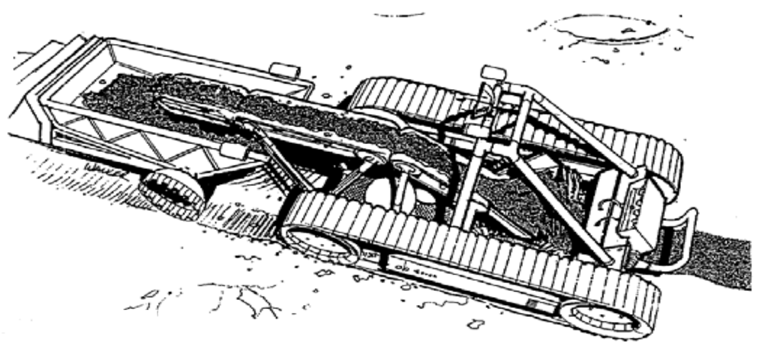
Regolith excavation & feed system unit. Consists of excavator (bucket wheel shown), auger, and crusher to move regolith from the entry port into the regolith processing unit with minimal loss of trapped volatiles.

Regolith Volatile Chamber. Will thermally process the regolith to extract all volatiles. If a nuclear isotope power unit is incorporated, heat from the isotope power unit will be used to reduce electrical power generation needs

Volatile separation, liquefaction, and storage unit. Will identify and measure all volatiles released. It will capture hydrogen, water, and/or other constituents previously identified separately in series.

Energy generation and distribution unit. Will include either dynamic radio-isotope power generation or fuel cell power generation for both thermal and electrical power to the LPRE

Lunar Miner & Hauler (Outpost)



Summary Data
Mass = 600 kg
Power= 5 kW
Volume = 8 m^3
Excavation Rate = 50 kg/hr

Operational Capability

The Lunar Miner & Hauler will support pilot lunar oxygen production plant regolith excavation needs. This dual function vehicle will be semi-autonomous and tracked or multi-wheeled to provide maximum traction and excavation force. Power is provided by regenerable fuel cells. The unit will incorporate a common mobile base unit with attachment locations for mining hardware and transport hardware changing depending on operation need. The mining functionality may incorporate a bucket or bucket wheel device for excavation and the hauling functionality may be as a bucket. Either or both may incorporate augers or conveyor belts for regolith transfer. Operation during lunar day is required, and possibly during lunar night (if Lunar Oxygen Pilot Plant operations are continuous). Excavation down to 1 m minimum with excavation rate of 50 kg/hr. Transport rate of 300 kg/load or 600 kg/24 hrs per hauler.

System Functionality

The Lunar Miner & Hauler will operate semi-autonomously with ground and crew interaction and redirection possible. The Lunar Miner & Hauler must autonomously coordinate excavation rates with the Lunar Oxygen Pilot Plant.

Reference Concept

The Lunar Miner & Hauler is designed to provide excavation and transport needs for pilot and full-scale oxygen production. The vehicle consists of 5 major elements, the mobile base unit, the excavation unit, regolith transport unit, regolith transfer unit, and mobile power unit. 2 Lunar Miner & Hauler vehicles will be needed in order to support

Mobile base unit. The mobile base unit will include autonomous navigation, communication, and command and control functions.

Excavation/Civil Engineering unit. Standardized attachment locations at the front and back of the mobile base unit will allow incorporation of different excavation concepts: bucket, and bucket wheel excavation are the two primary methods for excavation for regolith processing, bucket and back-hoe type devices for construction, and blades and box scrappers for road and landing pad construction.

Regolith transport unit. This will consist of a non-actuated or actuated bucket.

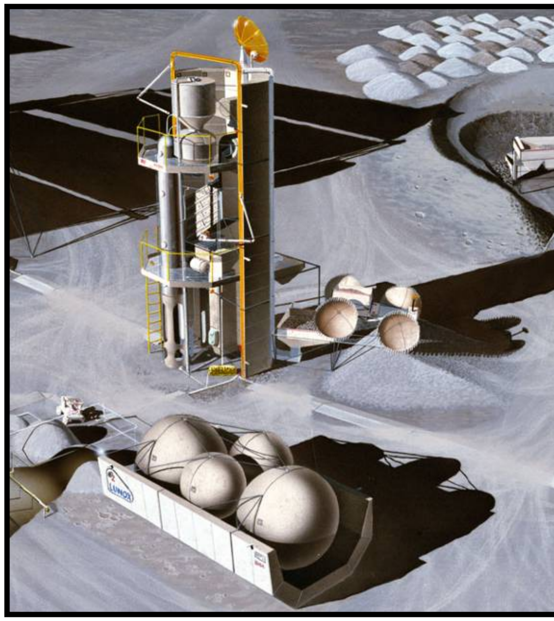
Regolith transfer unit. If a bucket excavation device is not utilized, the mining functionality will incorporate a separate regolith transfer unit to load/unload the regolith. The transfer unit may be an auger or conveyor depending on speed and requirements to minimize volatile losses.

Mobile power unit. The Lunar Miner & Hauler will incorporate a standardized mobile fuel cell power unit with disconnects to transfer fuel cell reagents and water with a central ISRU regeneration station/depot

Source

Based on analyses provided in
- Eagle Engineering Report 175, July 7, 1988.
- *Excavation Costs for Lunar Materials*, W.D. Carrier, 1979.

Lunar Oxygen Pilot Plant (Outpost)



Summary Data

8 MT O_2/yr
Mass = 800 kg
Power = 15 kW
Production rate = 1.14 kg/hr

Liquefaction & Storage of O_2
Mass = 200 kg (or lander tanks)
Power = 1.25 kW (liquefy)

Duration = 3 year min.

Operational Capability

The Lunar Oxygen Pilot Plant (LOPP) will produce, liquefy, and store a minimum of 1 kg of oxygen per hour. Regolith delivery to the LOPP will be provided via the Lunar Miner and Lunar Hauler. The LOPP will operate autonomously. Depending on the power source, LOPP will operate either continuously (nuclear) or only during lunar day with lunar night survival (solar).

System Functionality

The LOPP will provide all of the functions for self-sufficient operation, except for regolith delivery. Functionality required include the ability to pre-condition and deliver regolith to an oxygen extraction processing chamber, separate and store evolved oxygen, and remove processed regolith before entry of new pre-conditioned regolith.

Reference Concept

The LOPP will provide oxygen at a rate of either 8 MT/yr to support Lunar base operation and ascent vehicle refueling. The LOPP will consist of three major elements, the regolith inlet/outlet feed system unit, regolith processing unit, energy generation and distribution unit, and oxygen separation, liquefaction, and storage unit.

Regolith inlet/outlet feed system unit. Consists of pressurized hoppers, augers, and crushers to move regolith from the entry port into the regolith processing unit with minimal loss of trapped volatiles. Also removes processed regolith without loss of oxygen produced.

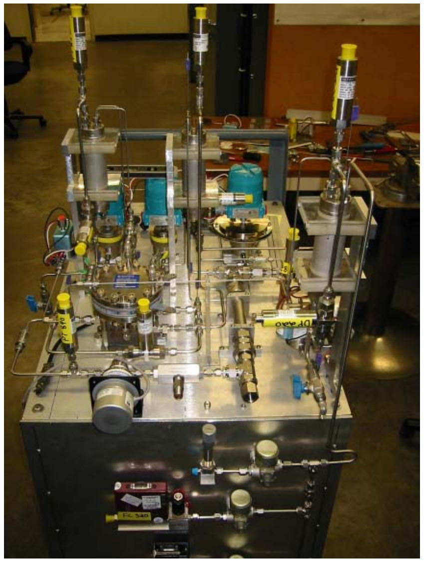
Regolith processing unit. Will process the regolith to extract oxygen. The regolith processing technique utilized will be based on results from Lunar Chemical Processing & Storage Demonstration(s)

Oxygen separation, liquefaction, and storage unit. Will liquefy and store all the oxygen produced from the processing chamber for use during the mission. Estimated mass, volume, power for the liquefaction and storage unit are: 165 kg system mass, 1250 W input power, 3.1 m^3 tank volume, 6.4 m^2 radiator area. These numbers are part of the summary data within the graphic.

Source

Eagle Engineering Report 155, July 7, 1988
*Volume based on LSAM cargo volume
Liquefaction and storage mass/power provided by KSC/YA

Lunar Water Processing Pilot Plant (Outpost)



Summary Data

8 MT O_2/yr
Mass = X kg
Power = X kW
Production rate = 1.14 kg O_2/hr & 0.15 kg H_2/hr

Liquefaction & Storage
O_2 tank mass = 200 kg (or lander tanks)
H_2 tank mass = 800 kg
Power = 1.25 kW (O_2 liquefy)
Power = 9.5 kW (H_2 liquefy)

Duration = 3 year min.

Operational Capability

The Lunar Water Processing Pilot Plant (LWPPP) will produce, liquefy, and store a minimum of 1 kg of oxygen and 0.15 kg of hydrogen per hour. Water delivery to the LWPPP will be provided via the Lunar Polar Resource Extractor (LPRE). The LWPPP will operate autonomously. Depending on the power source, LWPPP will operate either continuously (nuclear) or only during lunar day with lunar night survival (solar).

System Functionality

The LWPPP will provide all of the functions for self-sufficient operation, except for water delivery. Functionality required include the ability to receive and store water from the LPRE, electrolyze water into oxygen and hydrogen, liquefy and store oxygen and hydrogen, and transfer both cryogens to the Lunar Mobile Cryo Supply unit

Reference Concept

The LWPPP will provide oxygen at a rate of either 8 MT/yr to support Lunar base operation and ascent vehicle refueling. Hydrogen produced as part of the electrolysis process will be liquefied and stored for production of methane or other uses. The LWPPP will consist of three major elements, the regolith inlet/outlet feed system unit, regolith processing unit, energy generation and distribution unit, and oxygen separation, liquefaction, and storage unit.

Water collection and storage. Consists of tanks, pumps, valves, and connectors to receive water from the LPRE and deliver to the water electrolysis unit

Water electrolysis unit. Consists of water preparation hardware, water electrolysis unit, gas dryers, and connectors to the Cryo storage and transfer unit

Cryogenic fluid storage & transfer unit. Will liquefy and store all the oxygen and hydrogen produced from the electrolysis unit. Estimated mass, volume, power for the liquefaction and storage unit for oxygen: 165 kg system mass, 1250 W input power, 3.1 m^3 tank volume, 6.4 m^2 radiator area. These numbers are part of the summary data within the graphic. Estimated mass, volume, power for the liquefaction and storage unit for hydrogen: 755 kg system mass, 9500 W input power, 6.2 m^3 tank volume, 51 m^2 radiator area.

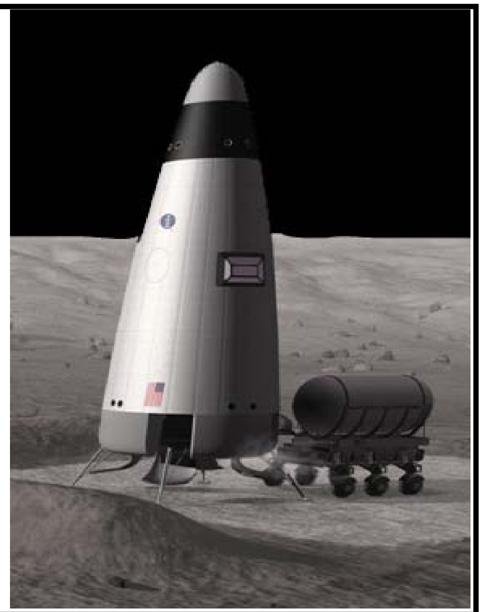
Source

Electrolysis and water storage mass provided by JSC/EP
Liquefaction and storage mass/power provided by KSC/YA

Lunar Mobile Cryo Supply (Outpost)

3.5 MT (O_2) Summary Data
Mass = 200 kg
Power = 1250 W (liquefy)
Vol = 3.5 m^3

0.44 MT (H_2) Summary Data
Mass = 800 kg
Power = 9500 W (liquefy)
Vol = 6.5 m^3



Reference Concept

The LMCS will provide oxygen storage capability of 3.5 MT. This system will provide active conditioning of the cryogens to support liquefaction and to maintain liquid cryogen temperatures to minimize boiloff. The storage tanks will be mounted into a rigid structure that can be set down on the surface or mounted onto a mobile platform. The LMCS will include transfer support hardware including pumps, valves, and dust insensitive couplings to support transfer to and from the LMCS.

The mobile platform will be the same as used for the miner/hauler

Operational Capability

The Lunar Mobile Cryo Supply (LMCS) will liquefy and store oxygen supplied from the LOPP (1.14 kg/hr) and support transfer of the liquid oxygen to surface assets and the Lunar Ascent Vehicle. The LMCS can operate autonomously, tele-operated, or via EVA astronaut. Depending on the power source, LMCS will operate either continuously (nuclear) or only during lunar day with lunar night survival (solar).

System Functionality

The LMCS will provide all of the functions for self-sufficient operation. Functionality required includes the ability to liquefy, store, and maintain cryogenic oxygen, to receive gaseous oxygen directly from the LOOP or liquid oxygen from other surface storage tanks, and deliver the oxygen throughout the lunar base and Lunar Ascent Vehicle as necessary.

Note: Mass and power numbers reflect cryogenic storage and maintenance only. Robotic platform data are not included.