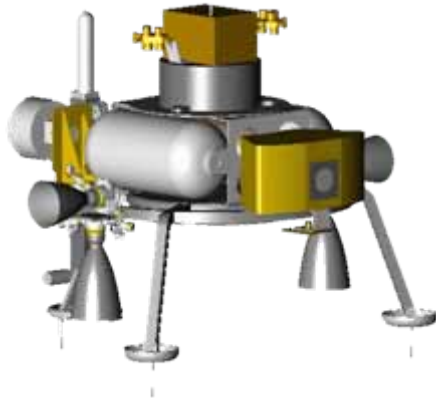




NASA In-Situ Resource Utilization (ISRU) Incorporation and Development Plans



***Presentation at Lunar Exploration
Analysis Workshop***

Oct. 2, 2007, Hobby Hilton, Houston

Jerry Sanders/JSC
Bill Larson/KSC

gerald.b.sanders@nasa.gov
william.e.larson@nasa.gov



Workshop ISRU Session Questions



1. What are critical ISRU, surface operation, and transportation related demonstrations that are needed to transition from establishment of an Outpost to long-term sustainability of robotic and human lunar exploration?
2. What opportunities are there for private sector space and/or international partnerships in proving and integrating ISRU and other capabilities required for Outpost sustainability into the current NASA Lunar Architecture? How do these opportunities support other international space agency and commercial space development objectives?
3. What precursor demonstration missions would significantly reduce the cost and/or risk of establishing the Outpost and long-term robotic and human exploration of the moon and beyond?



Two Key Questions*

- Are there activities of economic value that can be carried out by humans living for extended duration on the Moon?
- Can in-situ resources be used in significant ways to support those activities?

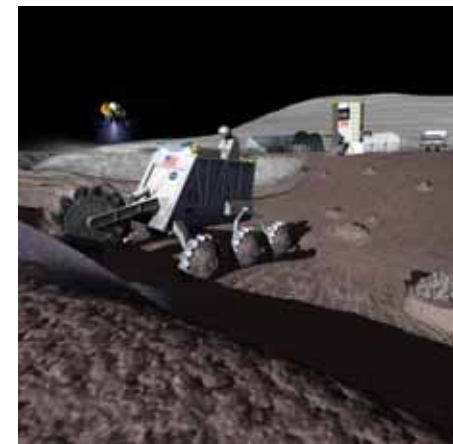
Economically Valuable Activities Feasible?

		No	Yes
Use of In-Situ Resources Feasible?	Yes	Space Tourism and Research	Space Settlement
	No	Research Only	Robotic or Human Tended Outpost

*Adapted from Harry Shipman, Humans in Space (1980) and obtained from John Logsdon



- **ISRU is a critical capability and key implementation of the VSE and sustained human exploration**
- **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**
- **Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired endstate**
- **Architecture is designed to be open enough to take advantage of ISRU from whatever source when available**





Three Pronged Approach to ISRU Development & Incorporation



- **Identify how ISRU fits into Architecture for Sustained human presence on the Moon**
 - Non-critical path initially with fall back strategy
 - Evolutionary with growth in:
 - Capability
 - Criticality
 - Ties to Mars
 - Ties to Space Commercialization

- **Build confidence in ISRU early and often**
 - Multiple generations of hardware and systems developed
 - Extensive ground and analog site testing for operations, maintenance, and interconnectivity
 - Robotic precursors if possible to reduce risk AND
 - Tie to common science objectives for regolith, mineral, and volatile characterization
 - Tie to long-term operations associated with Outpost deployment and operation

- **Early NASA involvement in all aspects of ISRU with transition to industry**
 - Ensures NASA is 'smart' buyer
 - Ensures lessons learned from ground and flight demonstrations are transferred to all of industry (unless pre-agreement established for commercialization aspect)
 - Ensures long-term industry involvement



What are critical ISRU, surface operation, and transportation related demonstrations that are needed to transition from establishment of an Outpost to long-term sustainability of robotic and human lunar exploration?

- What are the needs and roles for ISRU?
- When are they needed?
 - Before or after crew arrives?
 - Before sustained presence?
 - Before Outpost hardware PDR?

What precursor demonstration missions would significantly reduce the cost and/or risk of establishing the Outpost and long-term robotic and human exploration of the moon and beyond?

- Why are demonstrations needed?
 - Resource uncertainty (water, hydrogen, other)?
 - Risk reduction (technology, operations, and/or 'critical' path)?
 - Commercialization?
 - Mars Forward?



Crew Protection and Outpost Deployment

- **Landing area clearing, berm building and path preparation** reduces landing hazard/aborts, damage to hardware during delivery, and eliminates plume debris damage
- Radiation protection for crew with regolith or in-situ water
- Nuclear reactor and/or habitat burial

Consumable Production (In-Situ Oxygen, Water, Fuel)

- **Backup ECLSS and Eliminate need for Earth supplied consumable delivery**
 - Oxygen and water makeup for ECLSS closure, Habitat leakage, & EVA operations
 - Dissimilar functional backup eliminates ECLSS failure risks
 - Provide consumables for open systems (i.e. EVA)
 - Utilize trash as feedstock (solids, plastics, etc.) to make water and methane fuel
- **In-situ propellant production reduces risk & long-term cost of lunar transportation**
 - Eliminates mission loss due to leakage or increased boiloff with LSAM ascent stage
 - Adding/topping off ascent tanks above nominal increases sample payload to orbit
 - Fueling empty ascent tanks on surface substantially increases LSAM payload to surface capability
 - Oxygen (and fuel) for LSAM descent stage enables reuse of landers or surface hopping Sorties to other lunar locations
 - ISRU propellants can also be used for robotic sample return to increase payload and reduce cost

Integration into Lunar Outpost

- **Increased and more efficient Surface Power architecture with ISRU**
 - Centralized water processing & storage depot with Surface Power fuel cell reactant regeneration
 - Increased O₂ and H₂ regeneration and storage for nighttime power and mobile fuel cell power needs
- ISRU capabilities can be used to **offset uncertainties** in development and deployment of other Transportation and Surface Elements
- Once demonstrated and utilized early in the Outpost, ISRU production and use can be **expanded with increased confidence** in both ISRU and transportation elements



Possible Excavation Needs & Requirements for the Outpost



Excavation for Oxygen Production

- Evaluated a number of excavation options
- Parametrics presented are based on a front-end/overshot loader that scoops and dumps into bin on back of chassis
- If operate continuously, primary difference between small and large chasses is rate of drain on battery
 - Very inefficient to dig slowly/small amounts per scoop - lifting arm and dumping into bin is primary energy drain



Excavation for Outpost: Landing pads and berms

- Largest outpost emplacement excavation requirement over life of Outpost
- If landers are not moved, a new pad needs to be prepared *every 6 months*
- **Capability Manifested on 1st landed mission**



Excavation for Outpost: Habitat protection

- Multiple options if regolith shielding for radiation or thermal is desired
- Trenching and inflatable covers evaluated for excavation impact



Excavation for Outpost Emplacement

- Excavate ramp or hole for nuclear reactor emplacement/shielding
- Prepare pathways for transferring cargo from lander
- Prepare trenches for cables

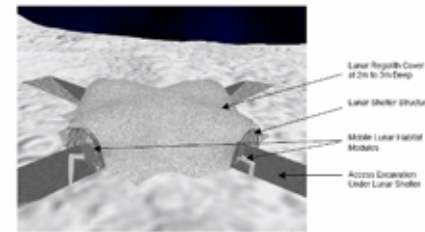
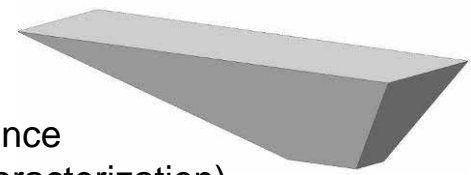


FIGURE 7. Conceptual Lunar Landing Site from the Lunar Lander Mission.

Excavation for Science

- Prepare trenches for subsurface geologic/stratigraphy access for Science
- Core extraction drilling for subsurface sample acquisition (resource characterization)
- Site preparation for antenna deployment





ISRU Consumable Production for Lunar Architecture



▪ O₂ Production from Regolith

- 2 MT/yr production rate for surface mission consumables – 1 MT/yr for ECLSS/EVA and 1 MT/yr to make water
- **Capability manifested on 6th landed mission (before start of permanent presence)**
- Increased production to 10 MT/yr during Outpost operation could also support refueling 2 ascent vehicles per year to further increase payload delivery capability

▪ In-Situ Water Production

- Scavenge minimum of 55 kg of hydrogen (max. ~252 kg) from each LSAM descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water
- Polar water extraction not evaluated in Lunar Architecture Phase II effort. Not needed unless large scale in-situ propellant (O₂ & H₂) production is required

▪ In-Situ Methane Production

- Pyrolysis processing of plastic trash and crew waste with in-situ oxygen can make methane
- Capability supports LSAM Ascent ‘top-off’ in case of leakage, power loss, or increased payload to orbit

ISRU Processing Requirements	kg/yr (min.)
Oxygen Production	
For ECLSS & EVA	1000
For Water Production	800
For LSAM Ascent Propulsion	7600
Water Production	
For ECLSS & EVA (from in-situ O ₂ + Scavenged H ₂)	900
Required H ₂ Scavenged from LSAM Descent Stage	100
For radiation shielding (*one time production need)	1000 to 2000*
Water Electrolysis	
For ISRU	1125
For Night time Power	7335
For Pressurized Rover Power (45 kg/mission)**	1260
Methane Production	
For LSAM Ascent Propulsion (max)	2160

** 28 excursions per year with at least 1 MPU

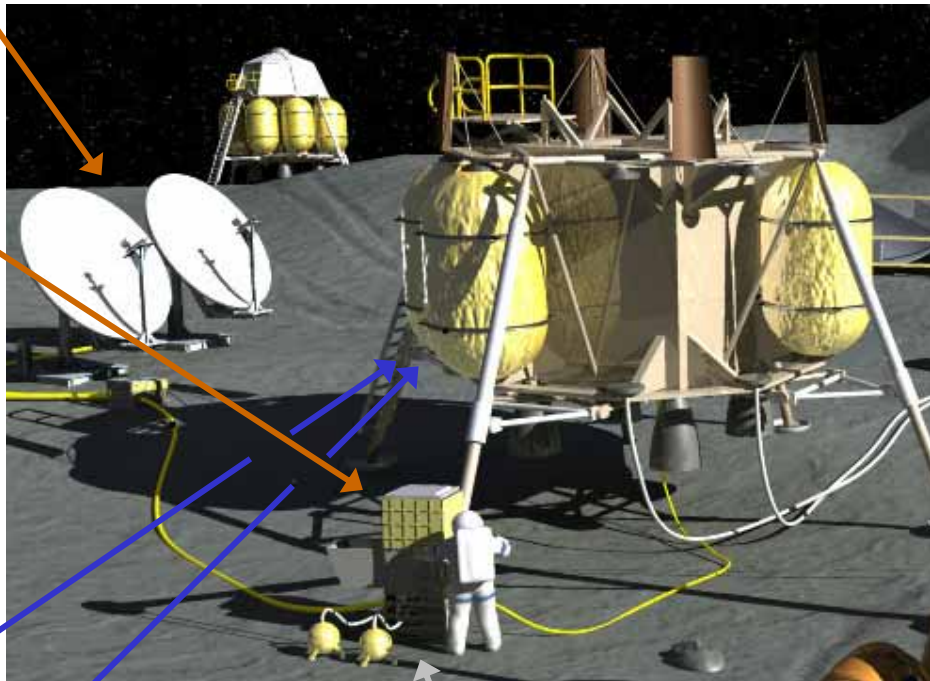


Lunar Architecture ISRU Systems & Technologies



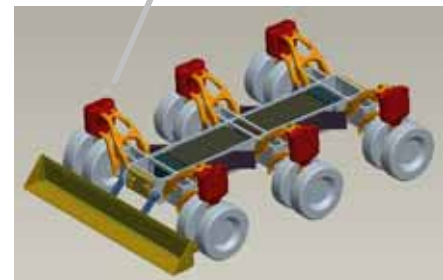
Solar Concentrators

- Lightweight or inflatable collectors
- Thermal management



Site Preparation, Berm Building, & Reactor Burial

- Surface Mobility
- High-cycle life, high-power density power systems
- End effectors w/ dust tolerant mechanisms
- Autonomous control



Small vs Large Rovers



Regolith Excavators/Haulers

- Surface mobility platforms
- High-cycle life, high-power density power systems
- End-effectors w/ dust tolerant mechanisms
- Autonomous control



Oxygen Extraction from Regolith

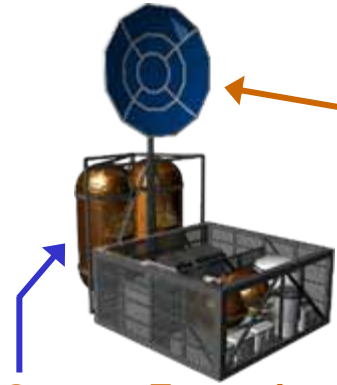
- Solid/gas processors
- Water electrolysis
- CO₂/methane processors & reagent regeneration
- Contaminant removal
- Thermal management & Radiators
- Dust tolerant sealing

H₂ Scavenging to Make Water

- Dust tolerant O₂ disconnects
- Dust tolerant H₂ disconnects

Oxygen Storage-Transfer

- High pressure O₂
- O₂ cryocoolers
- Liquid O₂ storage
- Thermal management
- Dust tolerant O₂ disconnects



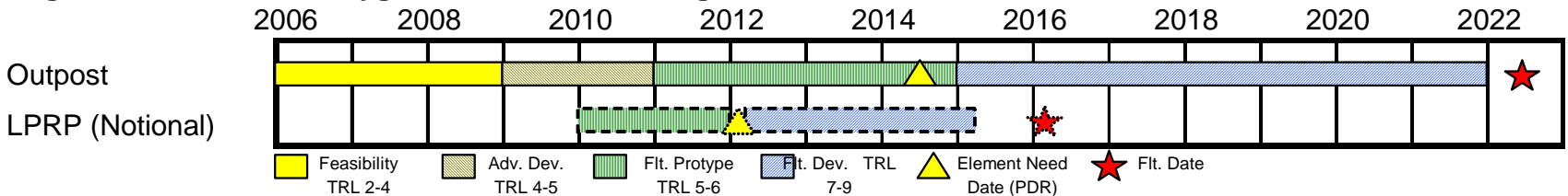


ISRU Development & Integration Strategy

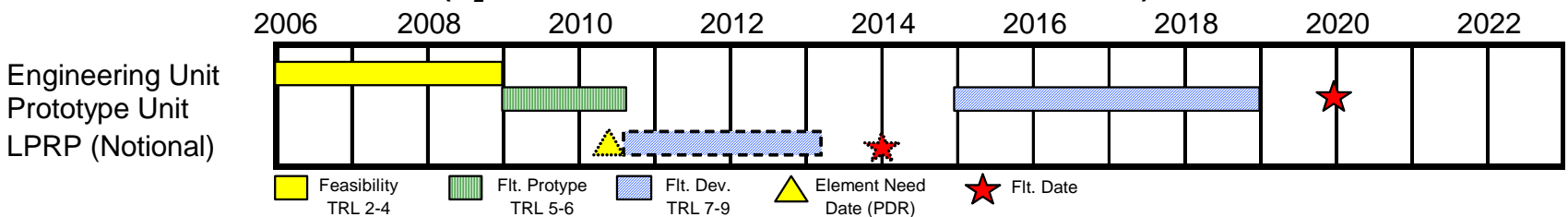


- **Develop ISRU through phased ground development without requiring LPRP missions**
 - LPRP missions would reduce risk of resource, process, and environment uncertainties that ground facilities could not adequately replicate
 - Technology and System development tasks be directed at Outpost applications but will also anticipate (not preclude) possible LPRP scale applications
- **ISRU Technology and Systems developed in 4 Phases (2-3 years each phase)**
 - Phase I: Demonstrate Feasibility
 - Phase II: Evolve System w/ Improved Technologies
 - Phase III: Develop 1 or more systems to TRL 6 Before Start of Flight development
 - Phase IV: Flight Development for Outpost
- **Be prepared to participate in robotic precursor missions should opportunity arise**
 - Site characterization, resource mapping, and/or ISRU precursor
 - Outpost ‘dress rehearsal’ mission

Regolith Excavation & Oxygen Extraction from Regolith



ISRU Precursor Demonstration (O₂ Production and Resource/Site Characterization)





ISRU System & Surface Operations Ground Demo Plan



2007

2008

2009

2010

2011

Site Preparation & Outpost Deployment

Inflatable Shelter concept



Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation



(At JSC & Hawaii)



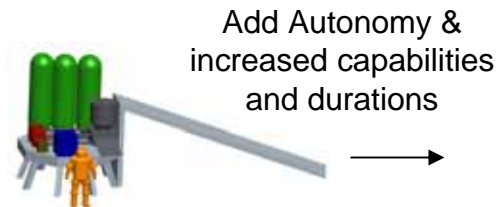
Add Autonomy & increased capabilities (ex. dig hole for reactor)

Oxygen Extraction from Regolith



Excavation and oxygen production from regolith with H₂ Reduction at 250 kg to 1000 kg per year rate for 1 to 5 days

(At Meteor Crater)



Add Autonomy & increased capabilities and durations

Excavation and oxygen production from regolith using carbothermal reduction at 250 to 1000 kg per year with solar power

(At Meteor Crater or Hawaii if in-situ material can be used)

ISRU Precursor & Site/Resource Characterization



Integrate RESOLVE drill on CMU rover (At CMU)



Integrate complete RESOLVE package on CMU rover



Possible: (At Hawaii- permafrost)

1. Add Advanced Power system to Rover
2. Perform joint demo with ARC K-10 rovers

Notional: Integrate other science instruments for prospecting on single platform (ex. GPR, Neutron Spec. etc.)



Previously Considered ISRU Demonstration Needs



	ISRU Demonstration	Rationale
1	Characterize hydrogen source at lunar poles (content, quantity, & location)	Large concentrations of hydrogen or water significantly affect architecture: location of Outpost, near-term self-sufficiency, and enable long-term large scale propellant production for reusable landers, cis-lunar transportation
2	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
3	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
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 found in #1)	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



Minimum Precursor Mission Needs before Outpost Establishment



Two critical aspects of lunar surface development and operations would significantly benefit from robotic precursor missions

1. Site selection:

- If long-term presence on the Moon is a goal (beyond just preparing for Mars), than understanding the hydrogen resources at the poles is critical before establishment of a lunar Outpost

2. Long-term operation on the Moon:

- Apollo provided 3 days max. of lunar surface hardware and operation experience. If development of EVA suits and surface system hardware that can operate continuously for months/years is a requirement, than long-term demonstration of hardware and systems on the Moon before final development of Outpost hardware is highly recommended

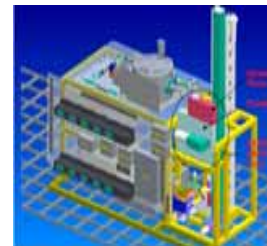


Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE)



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 (NORCAT)
- Significant university and Lunar science expertise



RESOLVE Engineering Breadboard Unit #1



RESOLVE-NORCAT Drill on Carnegie Mellon Univ. Scarab Rover

The five RESOLVE modules are:



➤ **EBRC - Excavation and Bulk Regolith Characterization (KSC/NORCAT/CSM)**

Provide capability of extracting samples of regolith down to 1 meter and determine geo-technical characteristics of the regolith.



➤ **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



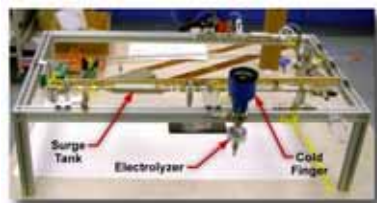
➤ **RVC - Regolith Volatile Characterization (KSC/GRC)**

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.



➤ **ROE - Regolith Oxygen Extraction (JSC/GRC)**

Demonstrate the ability to chemically extract oxygen from the regolith samples.



➤ **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



Notional Outpost Risk Reduction LPRP Mission (2016/2018?)



Mission is 'Dress rehearsal' for critical Outpost Elements

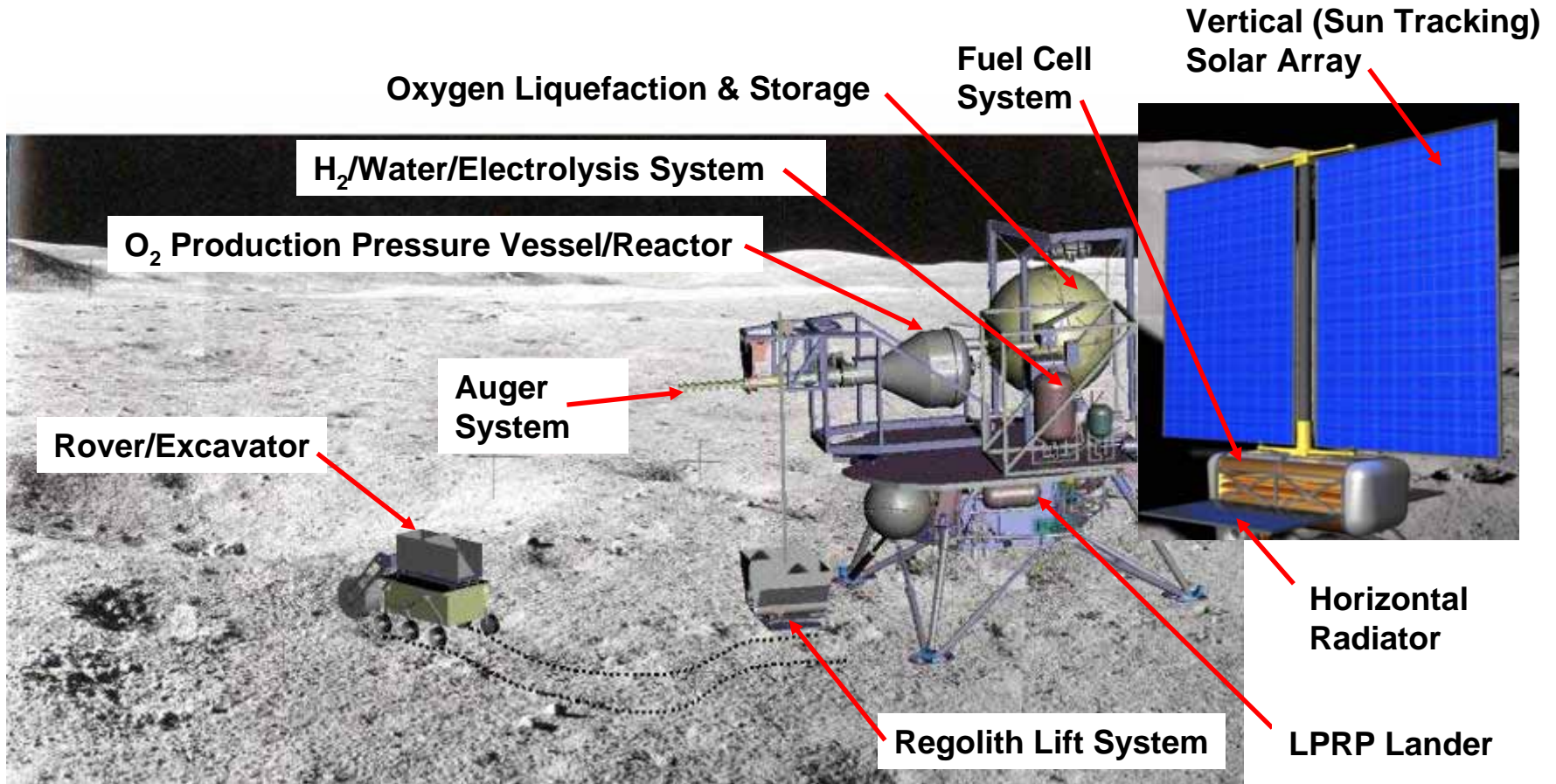
- **Six month nominal surface operations for performance, life, and operation experience, with goal of 1 complete year.**
- **Demonstrate surface mobility (Robotics):**
 - Relevant regolith excavation and transport techniques for oxygen production
 - Relevant navigation (hardware & software), operation, and life experience
- **Demonstrate oxygen extraction from regolith (ISRU):**
 - Oxygen production at scalable rate (0.5 to 1 MT O₂/yr rate) to Outpost 2022 deployment
- **Demonstrate surface power generation and storage at polar region (Power)**
 - Relevant scale power module unit for Outpost including solar array and fuel cell
 - Common water electrolysis unit for ISRU oxygen production and fuel cell regeneration
- **Demonstrate long-term storage of cryogenic oxygen (ISRU/EVA/Propulsion)**
 - Liquefaction and storage of 250 to 500 kg of cryogenic oxygen
 - 6 months of lunar day/night storage heatleak/boiloff prevention experience in dusty lunar environment for LSAM LO₂/CH₄ ascent vehicle, surface power module (12% mass savings over high pressure O₂), and EVA life support suit designers
 - Demonstrate liquid oxygen transfer from supply to receiver tank if payload mass/volume allows
- **Demonstrate heat rejection and thermal management at polar region (Thermal)**
 - 6 months minimum of radiator performance data in dusty lunar environment (with sensors)
- **Demonstrate ability to reduce life support logistics for Outpost (Life Support)**
 - GC/MS and/or habitat atmosphere quality sensors for oxygen purity characterization
 - Possible common water electrolysis unit for life support
- **Demonstration of Dust Mitigation techniques in conjunction with all demonstration hardware**
- **Integrated Surface Operation**
 - Demonstrate coordinated, semi-autonomous surface operations for minimum of 6 mo and up to 1 year
 - Demonstrated communications and Earth ground support operation and control



Notional Outpost Risk Reduction Robotic Precursor Mission

▪ Mission could be a 'Dress rehearsal' for critical Outpost Surface Elements

- Fly relevant Outpost Surface element (and LSAM) technology and hardware 6 to 8 years before Outpost deployment so that performance and lessons learned can be applied to the final Outpost design.
- Six month nominal surface operations for performance, life, and operation experience, with goal of 1 complete year



Notional ISRU mission graphic courtesy from LMA



Question #2



What opportunities are there for private sector space and/or international partnerships in proving and integrating ISRU and other capabilities required for Outpost sustainability into the current NASA Lunar Architecture? How do these opportunities support other international space agency and commercial space development objectives?



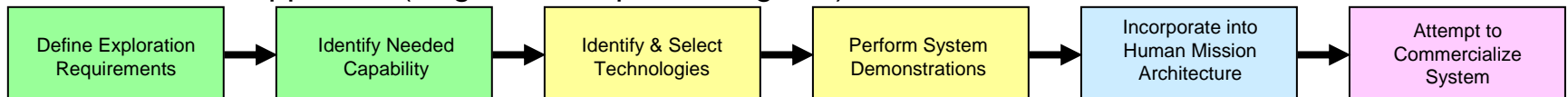
Approach to Commercializing ISRU



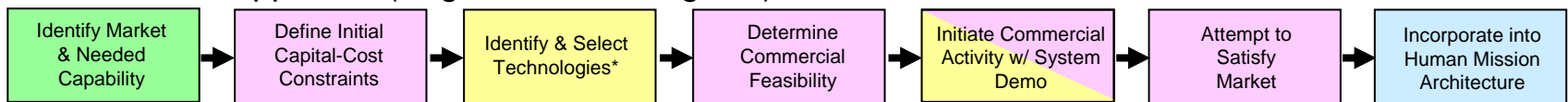
To 'commercialize' ISRU, markets besides NASA human exploration are required.

- Identify ISRU capabilities that could be of benefit to multiple customers (Science, National Security, Public Interest, Economy)
- Identify impediments to commercialization (technology, policy/regulations, risk, etc.)
- Initiate NASA/Government activities to promote ISRU commercialization
 - Infrastructure, research & development, coordination, etc.
- The 'Business Model' will drive the Missions; Early Human exploration ISRU demonstrations could:
 - Develop and demonstrate technologies & operations to reduce risk
 - Business models can accelerate/defer ISRU demo prioritization and timing

Traditional NASA Approach (Begin with Exploration goals)



Business Model Approach (Begin with Market goals)



*Selection of Technology is based on optimum cost not performance



- Most Space Resources-related Exploration Applications have Commercial Potential
 - Propellants, consumables, power system elements, building materials, fabricated parts and higher-order manufactured items

- Possible Market Areas for commercialized space ISRU in next 10 to 15 years if lunar Outpost is a long-term initiative
 - Science (NASA): lunar-based astronomical observatories
 - National Security (DOD, DOE):
 - [Eliminate dependence on foreign energy](#) (power beaming, Helium-3, etc.)
 - Eliminate dependence on foreign strategic metals (NEOs)
 - [Satellite refueling](#), space control, debris management
 - Earth and space surveillance
 - Public Interest (NOAA): Weather monitoring, Earth monitoring
 - Economy:
 - [Satellite delivery to orbit: LEO to GEO](#)
 - Space Commercial: communications & data, power, transportation, tourism/habitats
 - Earth Applications: mining, petrochemical, power, construction, powder, manufacturing

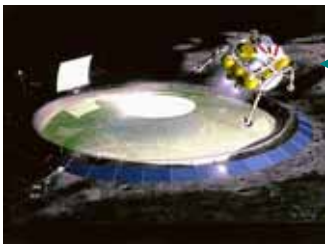


Near & Far Term Space Commercial Applications



Remote Sensing

- Earth viewing
- Astronomical observatories



Self-Sustaining Colonies

- Tourism
- Resort construction & servicing



Power Generation

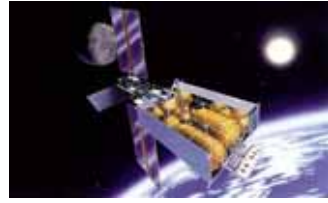
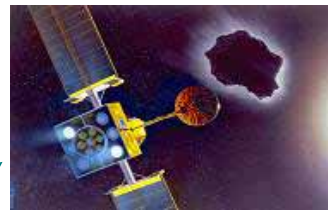
- Power beaming from lunar surface
- Helium-3



Cis-Lunar Transportation & Propellant

At Earth-Moon L1 for following:

- NASA Science & Human Exploration Missions
- Debris Management
- Military Space Control (servicing; moving, etc.)
- Commercial Satellite Delivery from LEO, Servicing, & Refueling
- Delivery of resources/products for Space Solar Power





- **NASA and other governments can reduce risk to space commercialization by:**
 - Supporting favorable legislature/regulation (tax incentives, property rights, liability, ITAR/Export Control, etc.).
 - Supporting R&D and demonstration missions thru partnerships
 - Providing ‘anchor tenancy’ to create market but not be sole customer
 - Provide payload opportunities

- **ISRU (consumables, construction, power generation, etc.) is only viable commercially if:**
 - The scope of the Outpost increases from initial crew of 4
 - Cis-lunar space transportation architecture becomes more reusable
 - NASA and other governments define commercialization strategy (‘exit strategy’) from start