In-Situ Resource Utilization (ISRU) And Lunar Surface Systems

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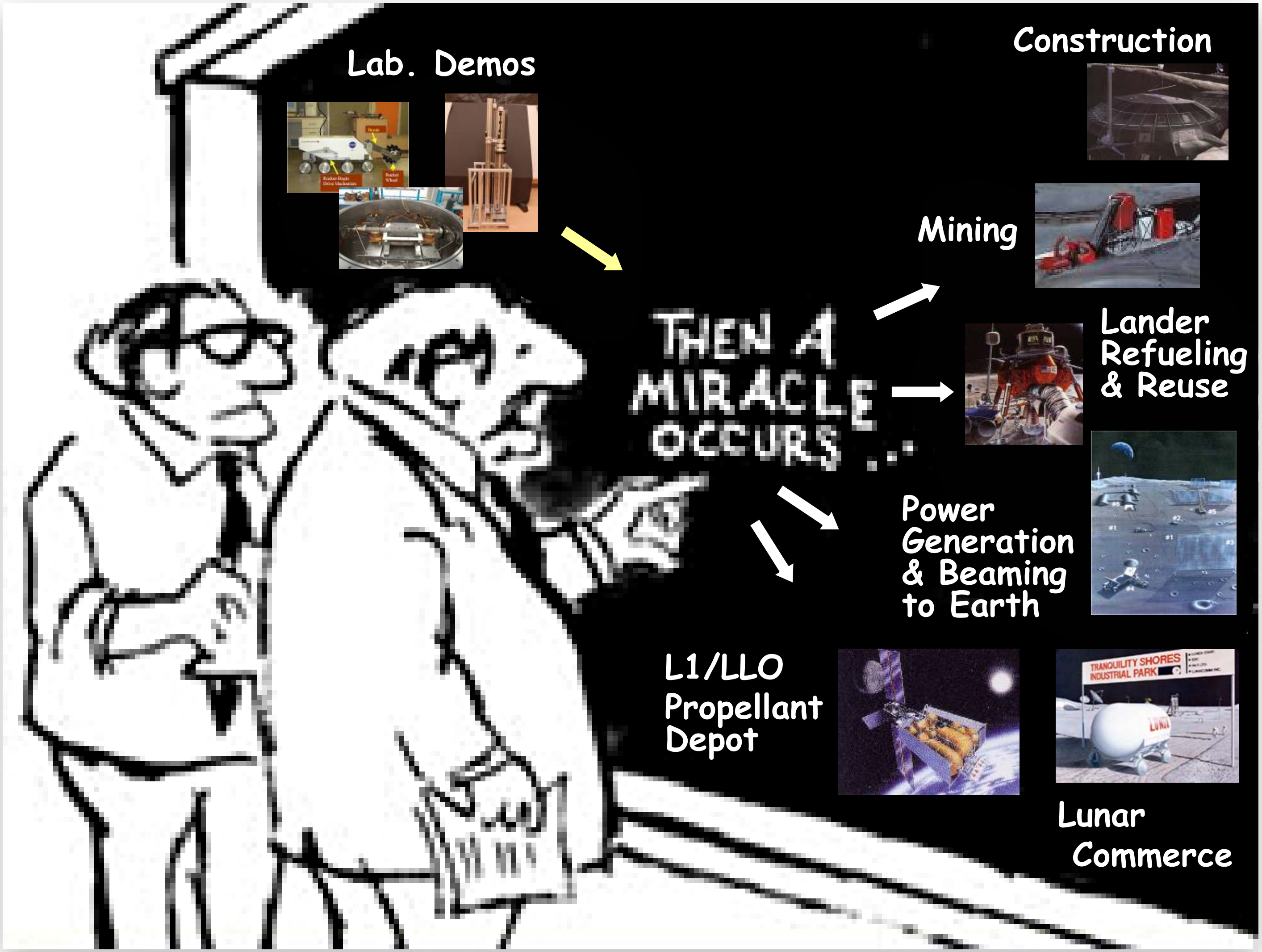
Previous ISRU Development & Implementation Roadmap



"I think more work is needed in this step."

Role of Moon in Human Exploration

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?

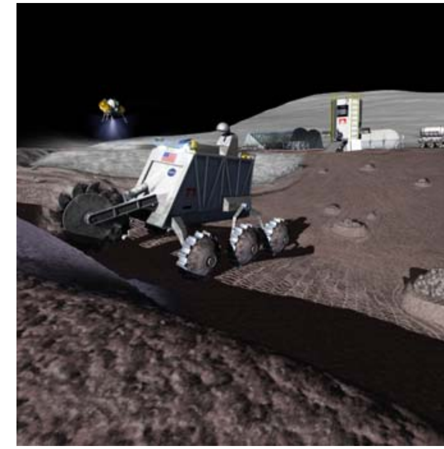
Economically Valuable Activities Feasible? (columns) / **Use of In-Situ Resources Feasible?** (rows)

	No	Yes
Yes	Space Tourism and Research	Space Settlement
No	Research Only	Robotic or Human Tended Outpost

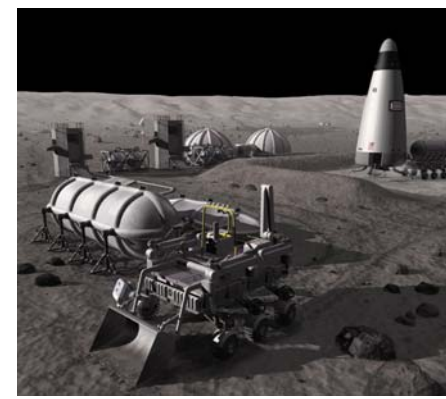
*Adapted from Harry Shipman, Humans in Space (1980) and obtained from John Logsdon

ISRU & NASA's Lunar Architecture

- **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 Ascent Vehicle 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) is manifested 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
  - Practice and demonstrate ISRU processes and techniques at every step

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

Overall Rank	Objective ID Number	Category	Short Title
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

Objectives of Lunar ISRU Development & Use

1. **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

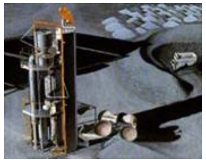
2. **Demonstrate ISRU** concepts, technologies, & hardware that reduce the mass, cost, & risk **for future Mars missions**
   – Excavation and material handling & transport
   – Volatile/hydrogen/water extraction
   – Thermal/chemical processing subsystems for oxygen and fuel production
   – Cryogenic fluid storage & transfer
   – Metal extraction and fabrication of spare parts

3. **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

4. **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.

5. **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, etc.) – link to Science objectives if possible
- 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.)

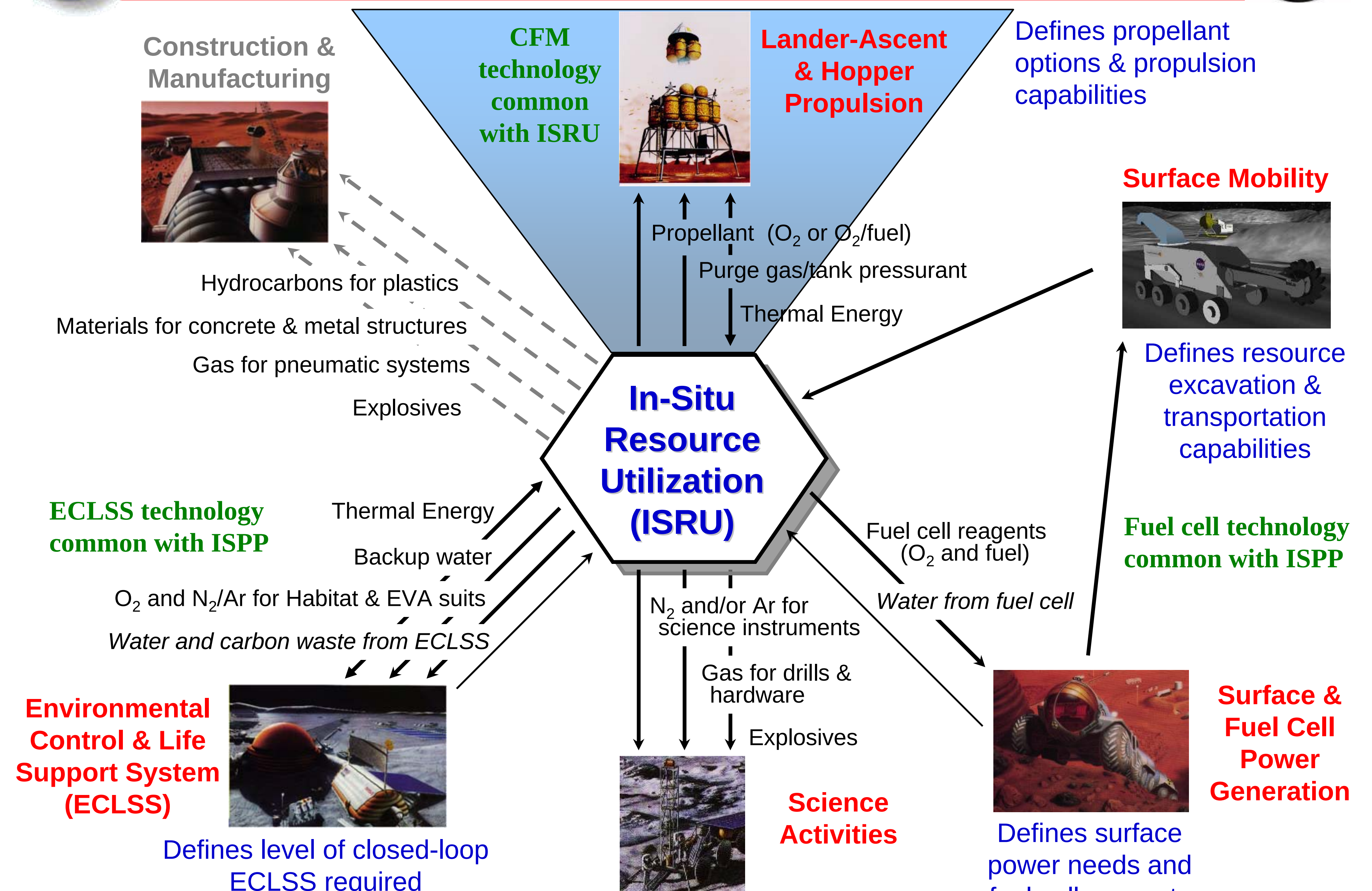
Mid-Term ISRU Capabilities - Exploration growth ("Hub & Spoke")

- Propellant production for LSAM, robotic sample return, or propulsive Hopper from Outpost
- Consumables for Pressurized rover
- 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 (^3He) mining, etc.

Critical ISRU Connectivity



Design & Implementation Impacts of ISRU on Outpost Elements

- **Life Support**
  - Degree of closed-loop air/water cycle and technologies/capabilities required depends on availability of ISRU water and oxygen. (ex. trade ISRU supplied water for 'dirty' water for propellant production)
  - Possible common water and air processing technologies and hardware
  - Amount of logistics required from Earth per year, size/mass of logistics carrier, and delivery rate
  - Disposal of trash and plastic waste – possible ISRU water, fuel production, and fabrication/repair feedstock by processing with ISRU oxygen

- **Extra Vehicular Activity (EVA)**
  - Liquid oxygen (LO_2) vs high pressure oxygen for Portable Life Support System (PLSS). LO_2 considered for PLSS only if available from ISRU
  - Water cooling/venting vs alternative cooling for PLSS. Availability of ISRU water or LO_2 could impact logistics and design
  - Amount of logistics required from Earth per year, size/mass of logistics carrier, and delivery rate

- **Surface Habitat & Mobile Power**
  - Consumable amount and storage concept for fuel cell reactants for night time power system (high pressure oxygen vs LO_2) different if ISRU is available (12% mass savings for LO2)
  - System capability to regenerate fuel cell reactants for surface mobility units (increase size of ISRU water electrolysis and storage system vs separate dedicated system)

- **Lunar Lander (LSAM) Propulsion**
  - ISRU O_2 (and possibly CH_4) enables resupply ascent vehicles
  - Use of LSAM descent tanks for ISRU storage minimizes downmass

- **Outpost Layout, Deployment, and Surface Operations**
  - Mobile Regolith transport systems for propellant/consumables production plant can double as road graders, landing site groomers, regolith shielding/insulating structure builders, etc

Lunar ISRU Development & Mission Strategy

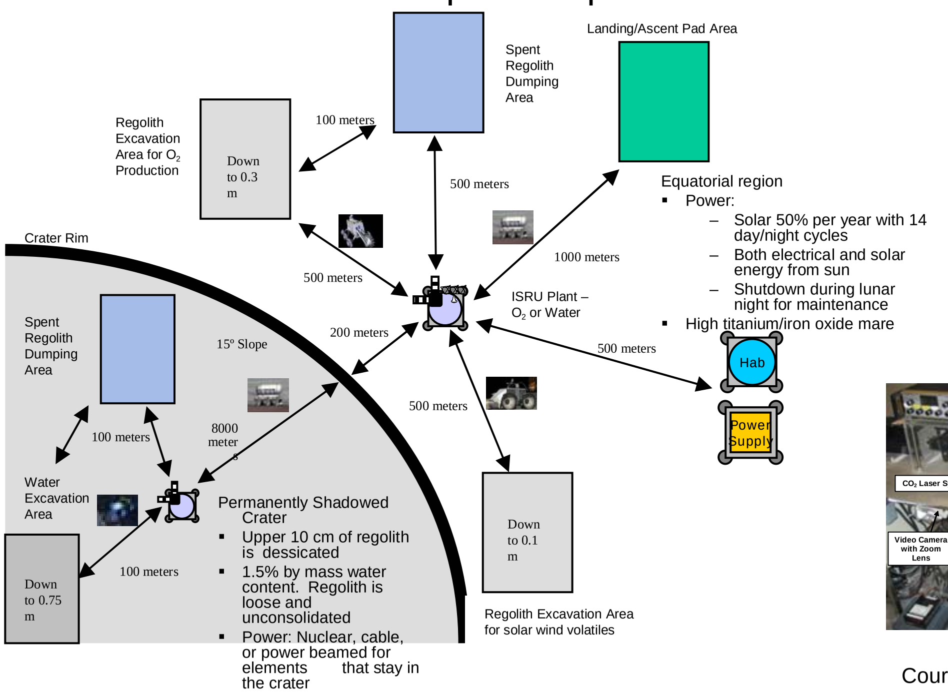
- **LRO/LCROSS missions provide critical data for ISRU and water resource development and implementation strategies for the lunar Outpost**
  - LRO provides locations of primary interest for resource prospecting and slope/terrain information for mobility
  - Allows future global understanding of resource potential at other locations after 'ground truth' mission has been performed
  - LCROSS could provide early evidence of water on the Moon
- **For minimum implementation risk, Lunar ISRU should be demonstrated and incorporated into the Lunar architecture in 3 Phases:**
  - Phase 1 Proof-of-concept & Concept Validation
  - Phase 2 Risk Reduction for Outpost (1/10th Outpost scale min. & 6 months operation – provides EVA capability demonstration before Outpost)
  - Phase 3 Outpost Deployment and Operation (full scale and redundant)
- **Lunar ISRU technology and system development must be tied to other Surface Systems**
  - Consumable storage and transfer architecture for life support, fuel cell power (nighttime and mobile), EVA, propulsion, and habitat ECLSS make-up and resupply
  - Common technologies and hardware to reduce cost and logistics
- **Lunar resource objectives require separate but integrated development paths**
  - Oxygen extraction from regolith (anywhere on the Moon)
  - Hydrogen/water extraction (Polar region only)
    - If high concentration outside shadowed crater, evaluate resource extraction and use potential
    - If low concentration outside shadowed crater, perform prospecting in shadowed crater
  - Conversion of trash & plastics

Lunar Oxygen Production Overview

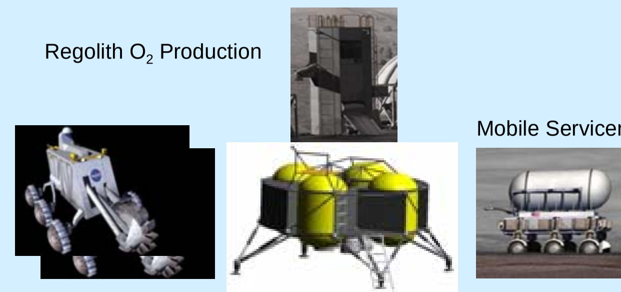
Production rate of 5 MT oxygen (O_2) & 1 MT water per year is baselined for the initial Outpost (2023) with buildup to 10 MT O_2 per year by 2027 with fuel:

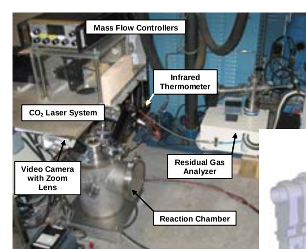
- **Initial capability supports EVA and habitat life support needs**
- **Build-up rate supports oxygen need for two LSAM ascent vehicles, EVA consumables, and habitat/life support backup**

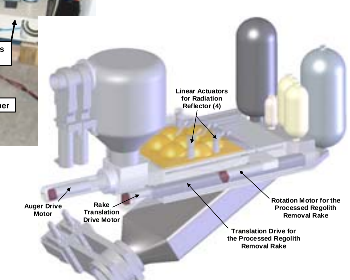
Level 0 Architecture & Outpost Requirements



Scenario 1: Oxygen Production from Regolith







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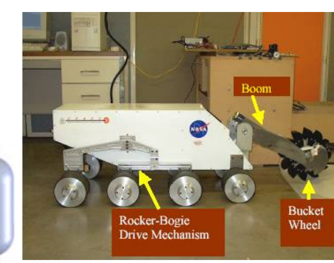
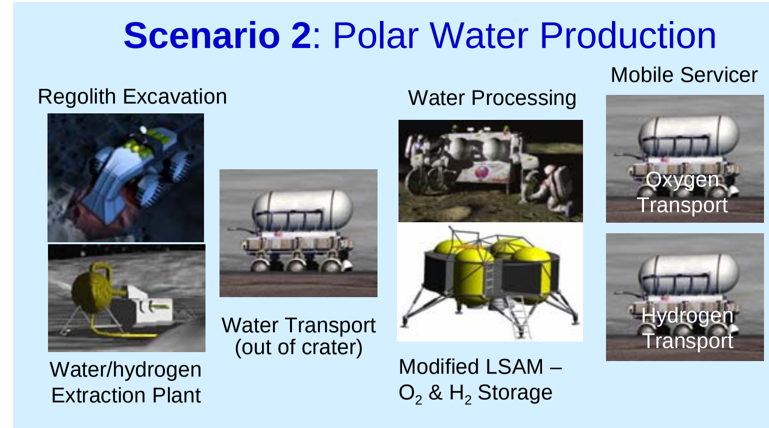


Courtesy of Colorado School of Mines

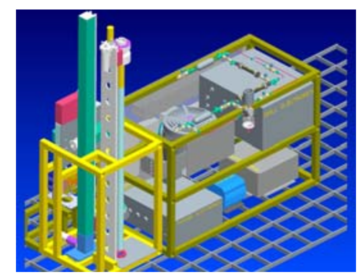
Mass of ISRU hardware required to produce 8 to 10 MT of oxygen per year is <2000 kg.

Lunar Volatile & Water Resource Overview

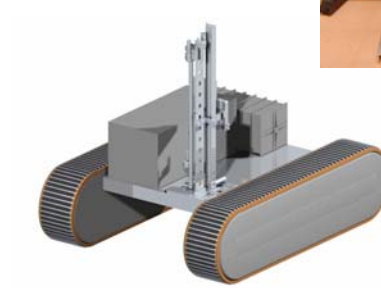
- **In-situ availability of water and hydrogen is of significant interest for human exploration**
  - Crew drinking/cleaning and degree of water processing required
  - Extra-vehicular activity (EVA) suit cooling
  - O_2 and H_2 from water for propulsion and fuel cells; also easily transferable to other 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

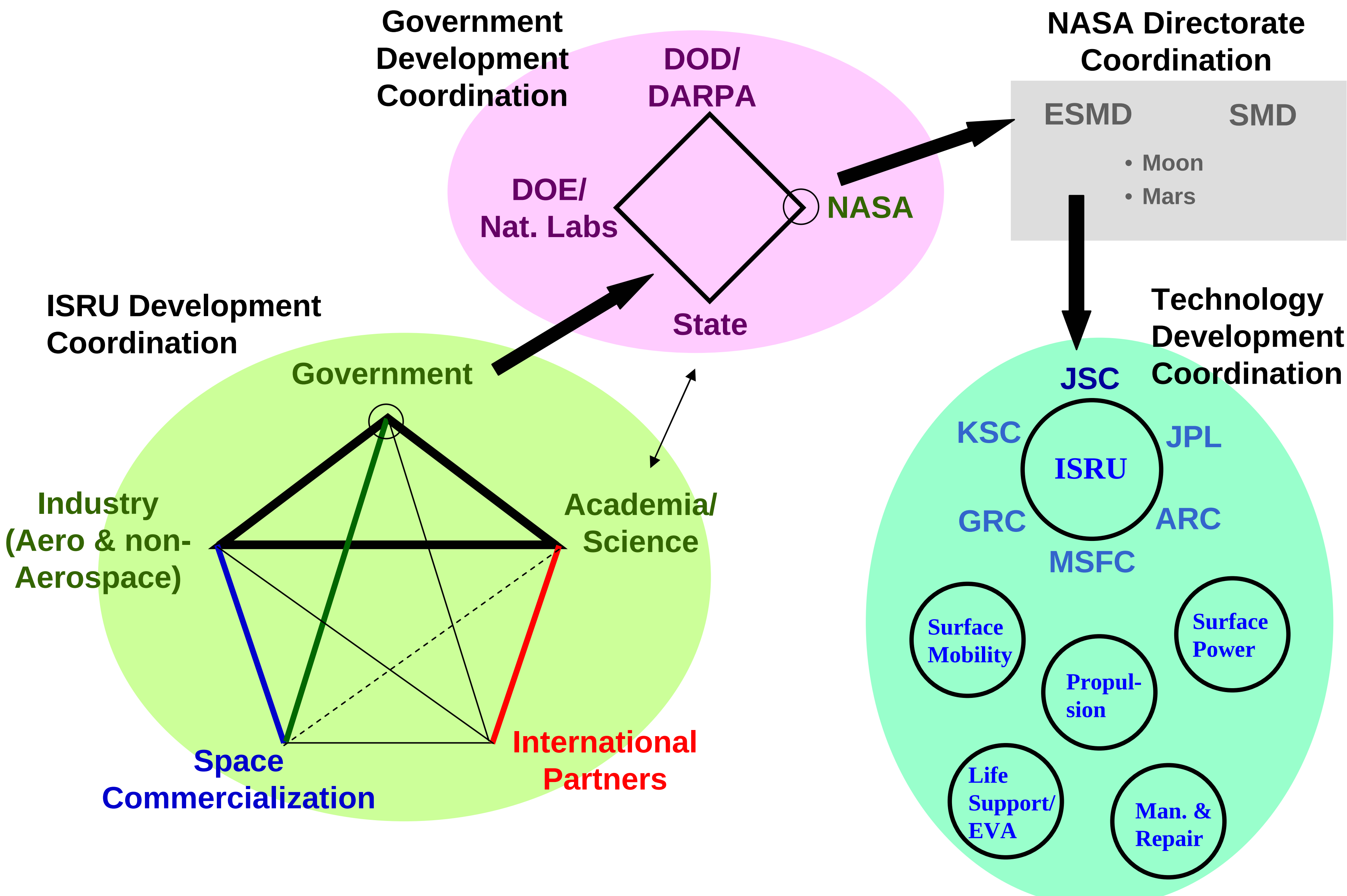


- **Currently developing resource acquisition, processing, and characterization hardware for possible use in future LPRP mission for science and exploration to determine:**
  - Regolith properties for future excavation and processing systems
  - Volatile constituents, amounts, and distribution
  - ISRU-related hardware performance on the Moon



➢ **Possible synergism with prospecting and extracting water on Mars for ISRU**

ISRU & Important Collaborations



ISRU Can Unite
Human Exploration, Science, & Space Commercialization

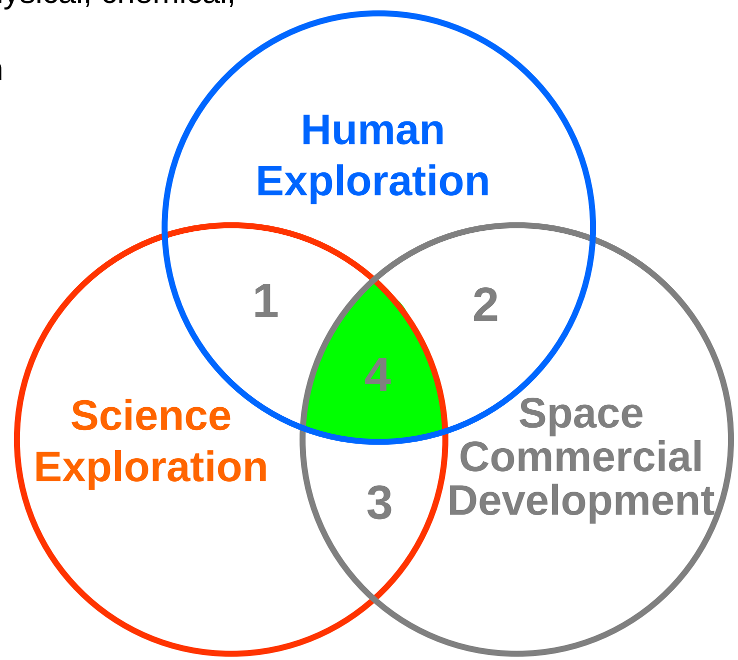
1. Joint Science/Human Exploration

Direct

- Remote & in-situ resource physical, chemical, and spatial characterization
- Environment characterization
- Resource/sample extraction and processing
- Human/robotic interaction
- Autonomous Operations

Indirect

- Access to bedrock and subsurface stratigraphy
- Extended missions
- Enhanced surface mobility
- Enhanced or increased power availability
- Increased payload or sample return size
- Infrastructure for long-term operations



2. Joint Human Exploration/ Space Commercialization

- Knowledge of resources and 'market' potential
- Risk reduction demonstrations
- High-leverage products with 'return on investment'
  - Propellants
  - Life support consumables
  - Power
- Robust and affordable transportation architecture
- Long-term operations and goals
- Infrastructure and capability growth

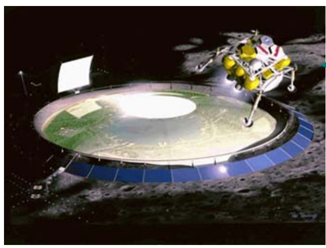
3. Joint Science/Space Commercialization

- Resource characterization/prospecting
- Resource/sample extraction and processing
- Infrastructure for long-term operations

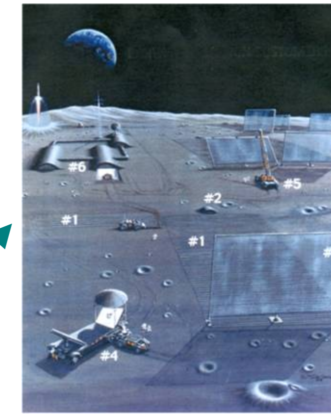
4. Needs Common to All

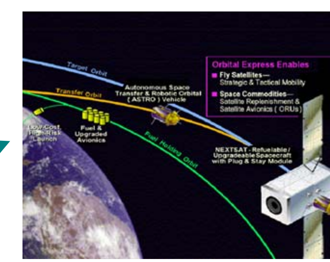
- **Resource information (sample return)**
- **Resource/sample extraction**
- **Maximize payload/return mass**
- **Maximize power availability**
- **Human/robotic interaction**
- **Reduced development and mission cost**

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





Path to Commercialization

- **Initiate NASA-Government Tasks to Enable Space Commercialization**
  - Demonstrations to validate concepts & build business case
  - Regulation reforms: tax incentives, property rights, liability, ITAR / export control
- **Utilize Multiple Methods for 'Commercializing' ISRU**
  - Traditional development BAA/Contracts
  - NASA Innovative Partnership Program (IPP)
  - Contract for 'services'
  - Government-Industry Consortiums (Comsat or Galileo)
  - Government-Industry "Infrastructure" Partnerships (railroad, air-mail, highways, etc.)
  - Prizes
  - Creation of Earth, LEO, and Lunar-based ISRU test & development laboratories
- **Establish a committee of representatives from NASA, industry, and academia**
  - Define the roles that NASA and Industry will have as space exploration matures.
  - Promote enactment of regulations and policy that enable short and long-term lunar commercialization goals
  - Initiate and establish policies, procedures and incentives to turn over Lunar infrastructure assets to industry so NASA can focus on exploring beyond the Moon.
  - Prioritize technology development & demonstrations which best meet goals of both reduced costs to NASA human exploration & space commercialization
  - Define scope and charter for Government-Industry Space Consortiums

➢ **Early engagement of NASA/commercial partnerships is required to maximize commercial benefits**

Customers & Connectivity

Customers & Stakeholders

- ESMD Technology Development Program
- Lunar Architecture and Mission Planners
- Lunar Robotic Precursor Program (LPRP)
- Constellation Program (LSAM & Surface Systems)
- Other US Government Agencies
- International Partners
- Commercial Space Industry

Requirements Connectivity	
Propulsion Systems	Propellant Quantity Propellant Type Residual Amount Storage Capability
Life Support/EVA Systems	Consumable Quantity Consumable Type Waste Products/Trash Storage Capability
Surface Mobility	Vehicle Size Terrain Mobility Capabilities Power Requirements Fuel Cell Reagent Quantity Fuel Cell Reagent Type
Surface Power	Daylight Power Amount Nighttime Power Amount Fuel Cell Storage Capability Nuclear Reactor Placement/Shielding
Habitat	Placement Shielding/Protection Assembly/Inflation Capability

Hardware Connectivity	
Propulsion Systems	Propellant Storage & Valving Solar Collectors
Life Support/EVA Systems	Consumable Storage & Valving Water Processing/Electrolysis Carbon Dioxide Processing Liquid/Gas Separation Solar Collectors Mobility Platforms
Surface Power	Consumable Storage & Valving Water Processing/Electrolysis Liquid/Gas Separation Solar Collectors
Science Instruments	Geotechnical Properties Volatile Characterization Mobility Platforms
Testing & Certification	Surface Analogs Environment Simulation Chambers Lunar simulants Simulant Bed Preparation

Conclusion: ISRU Strongly influences Architecture & Critical Technologies

- **ISRU is a critical capability and key implementation of the VSE**
  - 5 of top 40 Objectives identified for returning to the Moon; strongly tied to 7 more
  - ISRU is an integral part of all six Themes for returning to the Moon (Extend Human Presence, Exploration Preparation, Scientific Knowledge, Global Partnership, Economic Expansion, Public Outreach)
- **ISRU Strongly effects Outpost logistics, design and crew safety**
  - Potential to reduce logistics consumables for EVA/life support of 1000 to 4000 kg/year (2000 to 8000 kg w/ logistics carrier mass);
    - Significant payload impact if crewed LSAM down mass capability is only ~6000 kg.
  - Availability of liquid oxygen from ISRU allows EVA suits and mobile/night time power more volume and mass efficient (12% mass savings for power module)
  - Availability of ISRU oxygen/water provides functional redundancy to life support systems
  - Ability to move regolith could increase crew safety through increased radiation shielding, landing area clearing, and exhaust plume protection
  - Ability to produce oxygen (and fuel) for propulsion expands long-term surface exploration and payload delivery/return options
- **ISRU Strongly effects Outpost critical technologies**
  - LSAM ascent & descent propulsion
  - CO_2 and water life support system
  - EVA space suit portable life support system
  - Surface power reactant storage and regeneration for Outpost and mobile fuel cells
- **ISRU mass investment is minimal compared to immediate and long-term architecture delivery mass and reuse capabilities provided**

➢ **Investment in ISRU constitutes a commitment to the mid and long term future of human exploration**