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

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Tom Simon/JSC thomas.m.simon@nasa.gov
Kurt Sacksteder/GRC kurt.r.sacksteder@nasa.gov

In-Situ Resource Utilization (ISRU)

Contents:

What is ISRU?

What do our customers want?

ISRU Project Organization

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Existing and Potential Partnerships

What is Lunar In-Situ Resource Utilization (ISRU)?

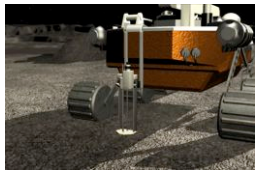
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

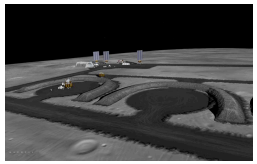
In-Situ Lunar Resources

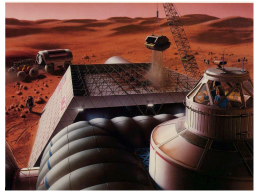
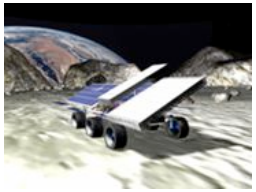
- **'Natural' Lunar Resources:**
  - Regolith, minerals, metals, volatiles, and water/ice
  - Sunlight, vacuum, thermal gradients/cold sinks
- **Discarded Materials**
  - LSAM descent stage fuel residual scavenging, tanks, material, etc. after landing
  - Crew trash and waste (after Life Support processing is complete)

Lunar ISRU Products and Services

- **Site Preparation and Outpost Deployment/Emplacement**
  - Site surveying and resource mapping
  - Crew radiation protection (In-situ water production or bulk regolith)
  - Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
  - Area and road clearing to minimize risk of payload delivery and emplacement
- **Mission Consumable Production**
  - Complete Life Support/Extra Vehicular Activity closure for Oxygen (O_2) and water
  - Propellant production for robotic and human vehicles
  - Regenerate and storage life support and fuel cell power consumables (in conjunction with Life Support and Power)
- **Outpost Growth and Self-Sufficiency**
  - Fabrication of structures that utilize in-situ materials (in conjunction with Habitats)
  - Solar array, concentrator, and/or rectenna fabrication (in conjunction with Power)
  - Thermal energy storage & use from processed regolith (in conjunction with Power)
  - Production of feedstock for fabrication and repair (in conjunction with Sustainability)





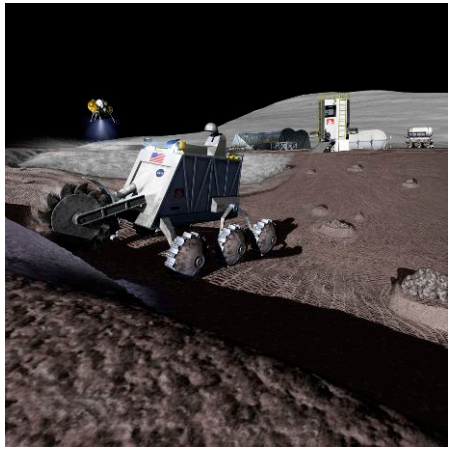
Vision for Space Exploration: ISRU is an Integral Part

- **ISRU Supports and Enables the four main Goals and Objectives of the U.S. Vision for Space Exploration (VSE)**
  - 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.

- **ISRU is integral to the success of all of the 'Themes' for Why we are going to the Moon?**
  - Extend sustained human presence to the Moon to enable eventual settlement
  - Pursue scientific activities to address fundamental questions
  - Use the Moon to prepare for future human missions to Mars and other destinations
  - Expand Earth's economic sphere to encompass the Moon, and pursue lunar activities with direct benefits to life on Earth.
  - Strengthen existing and create new global partnerships
  - Engage, inspire, and educate the public

ISRU: Decisions from Lunar Architecture Development

- 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



ISRU Roles, Needs, & Integration into Lunar Architecture

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

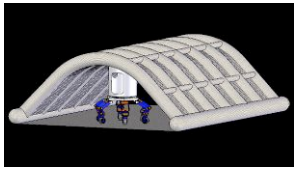
- **Increased and more efficient Surface Power architecture with ISRU**
  - Centralized water processing & storage depot with Surface Power fuel cell reactant regeneration
  - Increased O_2 and H_2 regeneration and storage for nighttime power and mobile fuel cell power needs
- ISRU capabilities can be 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



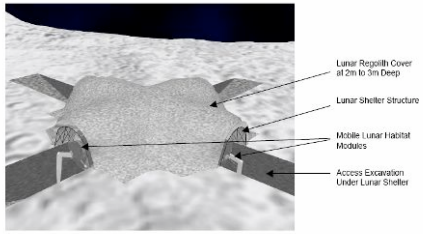


FIGURE 7. Completed Shelter Providing Protection for Mobile Lunar Habitat Modules.

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

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

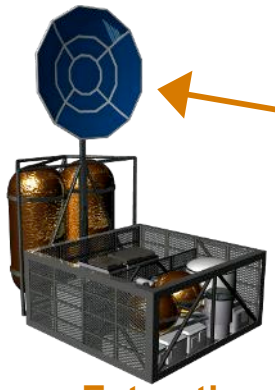
ISRU Consumable Production for Lunar Architecture

- **O_2 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 (O_2 & H_2) 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

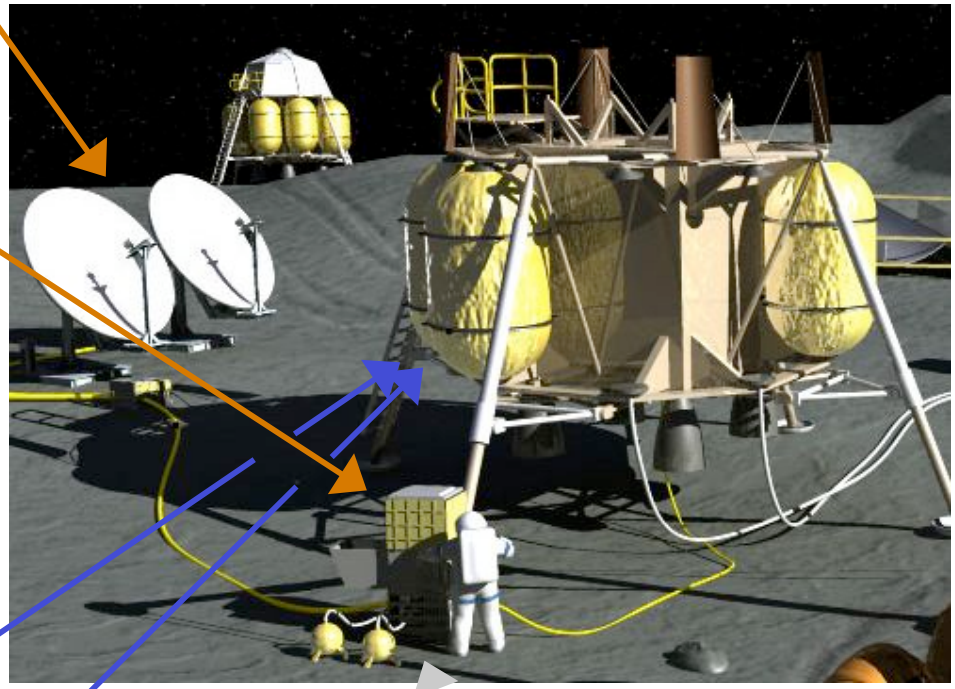
** 28 excursions per year with at least 1 MPU

Lunar Architecture ISRU Systems & Technologies



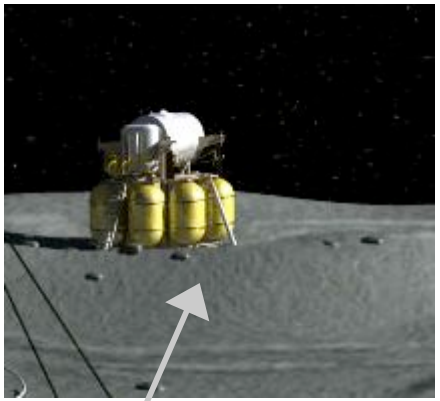
Solar Concentrators

- 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

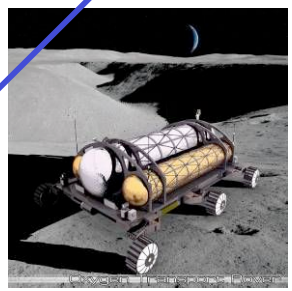


Oxygen Extraction from Regolith

- Solid/gas processors
- Water electrolysis
- CO_2/methane processors & reagent regeneration
- Contaminant removal
- Thermal management & Radiators
- Dust tolerant sealing

H_2 Scavenging to Make Water

- Dust tolerant O_2 disconnects
- Dust tolerant H_2 disconnects

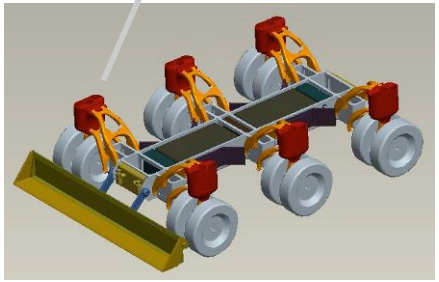


Oxygen Storage-Transfer

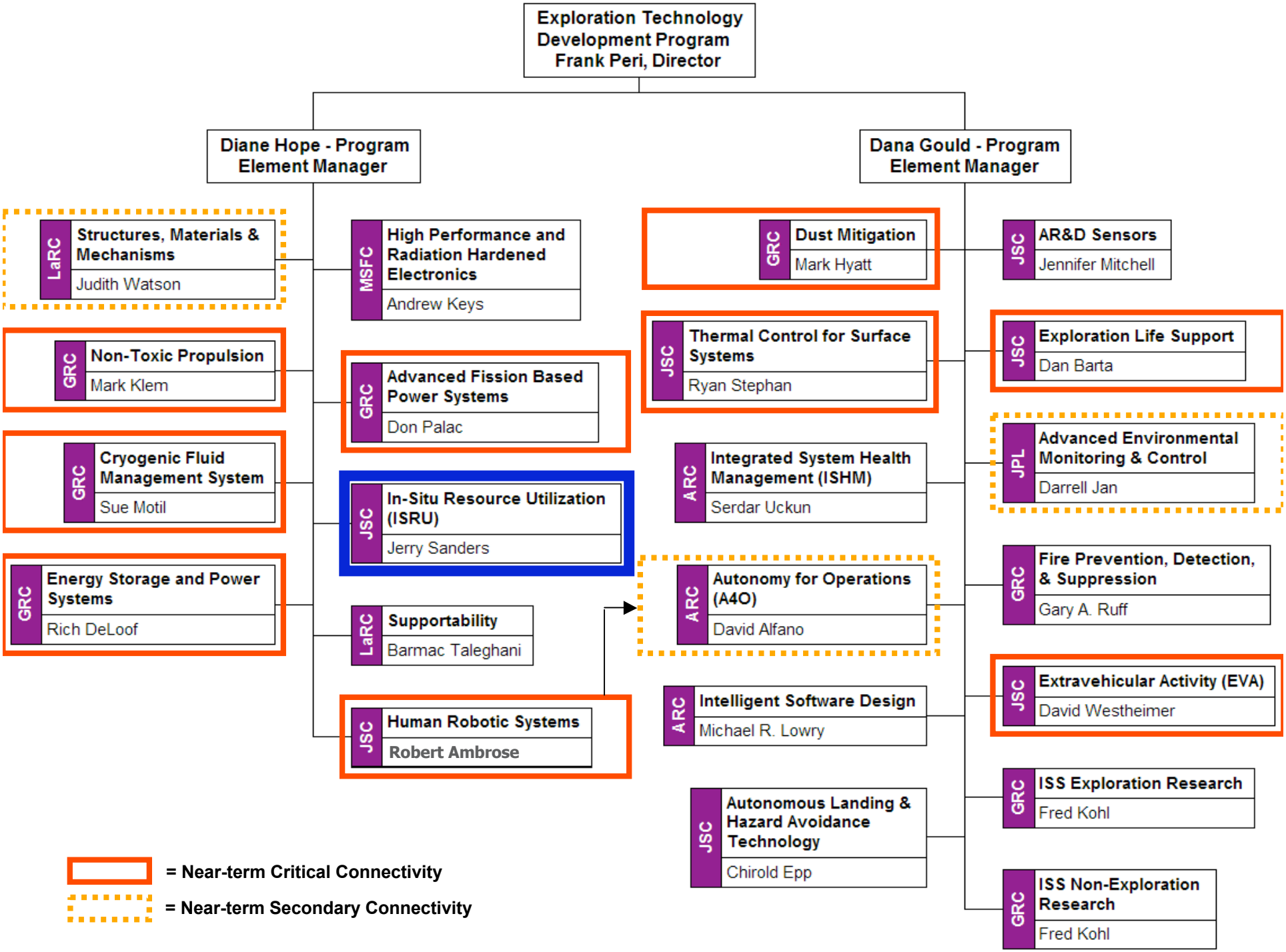
- High pressure O_2
- O_2 cryocoolers
- Liquid O_2 storage
- Thermal management
- Dust tolerant O_2 disconnects

Regolith Excavators/Haulers

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



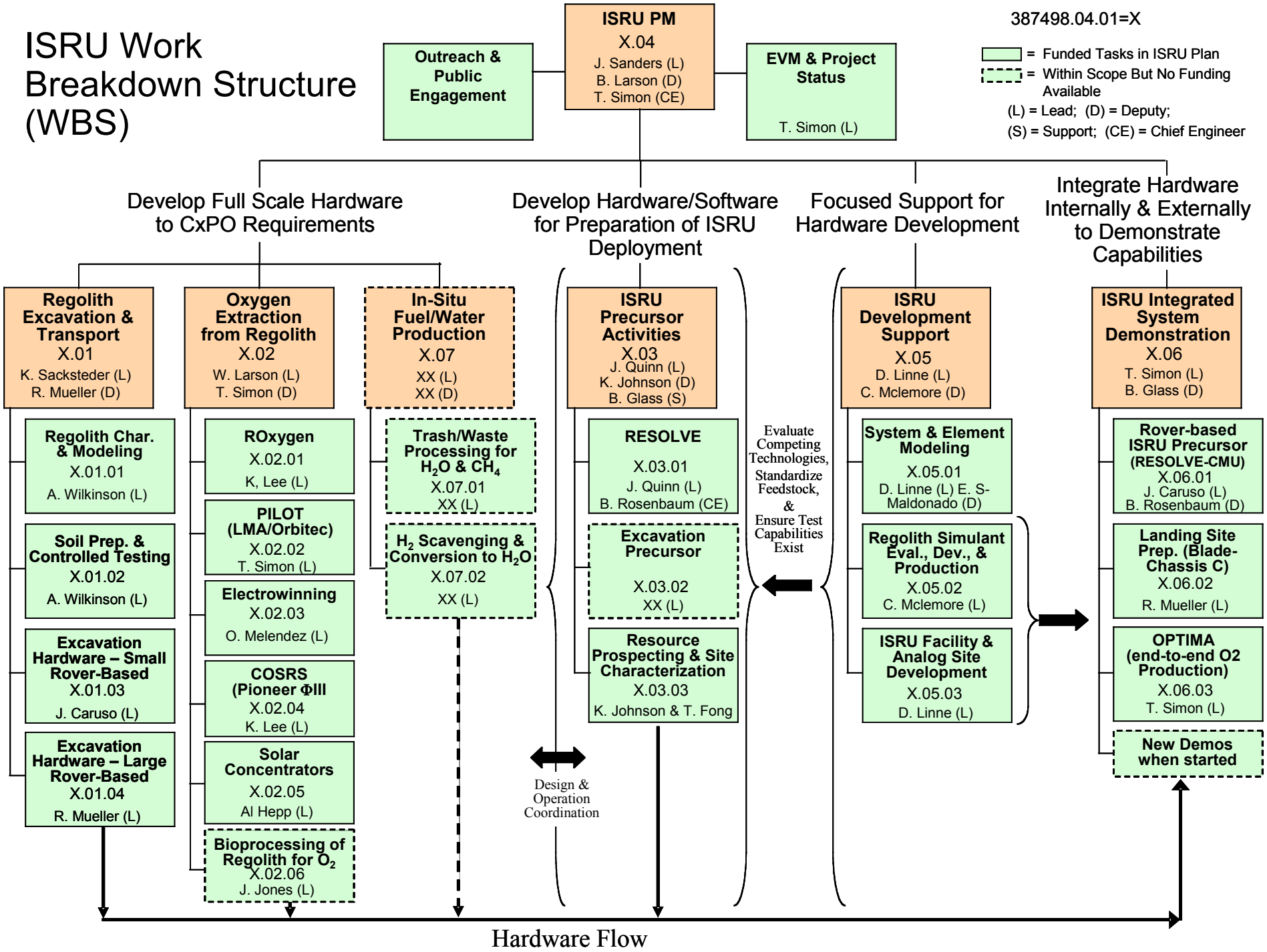
Small vs Large Rovers


Exploration Technology Development Program
Frank Peri, Director
Diane Hope - Program Element Manager
Dana Gould - Program Element Manager
LaRC
Structures, Materials & Mechanisms
Judith Watson
GRC
Non-Toxic Propulsion
Mark Klem
GRC
Cryogenic Fluid Management System
Sue Motil
GRC
Energy Storage and Power Systems
Rich DeLoof
MSFC
High Performance and Radiation Hardened Electronics
Andrew Keys
GRC
Advanced Fission Based Power Systems
Don Palac
JSC
In-Situ Resource Utilization (ISRU)
Jerry Sanders
LaRC
Supportability
Barmac Taleghani
JSC
Human Robotic Systems
Robert Ambrose
GRC
Dust Mitigation
Mark Hyatt
JSC
Thermal Control for Surface Systems
Ryan Stephan
ARC
Integrated System Health Management (ISHM)
Serdar Uckun
ARC
Autonomy for Operations (A4O)
David Alfano
ARC
Intelligent Software Design
Michael R. Lowry
JSC
Autonomous Landing & Hazard Avoidance Technology
Chirold Epp
JSC
AR&D Sensors
Jennifer Mitchell
JSC
Exploration Life Support
Dan Barta
JPL
Advanced Environmental Monitoring & Control
Darrell Jan
GRC
Fire Prevention, Detection, & Suppression
Gary A. Ruff
JSC
Extravehicular Activity (EVA)
David Westheimer
GRC
ISS Exploration Research
Fred Kohl
GRC
ISS Non-Exploration Research
Fred Kohl
= Near-term Critical Connectivity
= Near-term Secondary Connectivity

Three Pronged Approach to ISRU Development & Incorporation

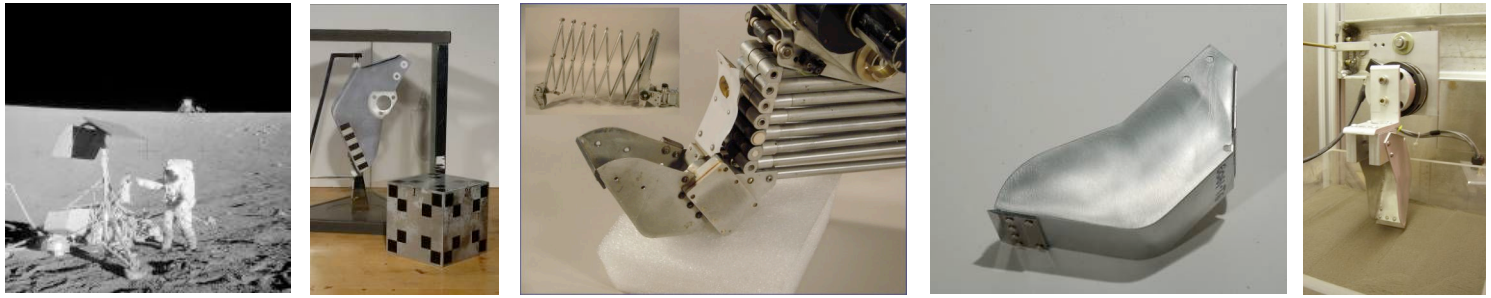
- **Identify how ISRU fits into Architecture for Sustained human presence on the Moon**
  - Non-critical path initially with fall back strategy
  - Evolutionary with growth in:
    - Capability
    - Criticality
    - Ties to Mars
    - Ties to Space Commercialization
- **Build confidence in ISRU early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

ISRU Work Breakdown Structure (WBS)



Lunar Regolith Excavation Development

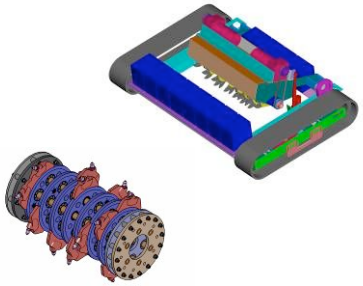
Soil Preparation and Controlled Testing



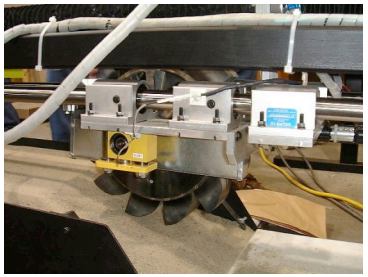
Surveyor Arm/Scoop Re-fabrication and Controlled Laboratory Testing at GRC

Excavation Hardware – Small Rover-based

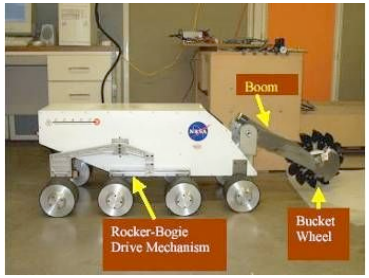
Cratos Small Excavator at GRC



Cratos w/ Hard Regolith Cutter Concept



Buckwheel Testing At NORCAT



Bucketwheel Excavator at CSM

Bucketdrum Excavator at LMA (IR&D)

Excavation Hardware – Large Rover-based

Chariot (Chassis C) Vehicle

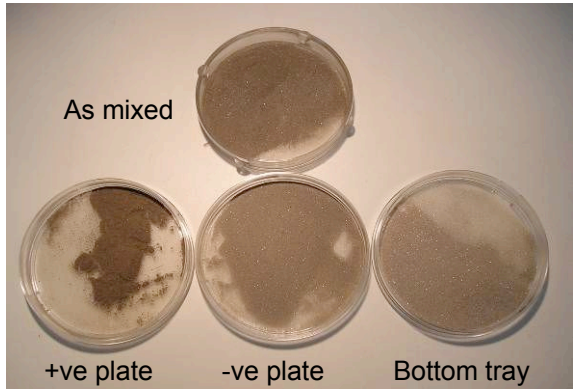
Area Clearing Blade on Chariot

Multi-purpose End-effecter on Chariot

ISRU Regolith Development, Mitigation, & Handling

Regolith Beneficiation

Regolith Iron-Oxide Beneficiation (KSC)



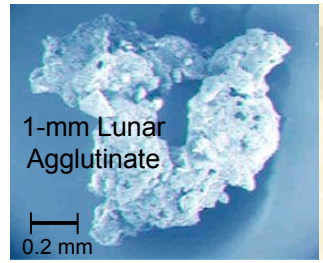
Beneficiated Regolith after 1st Pass (PTFE Charger)

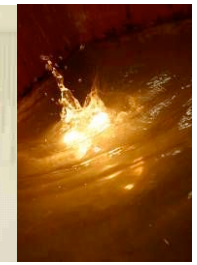
Feldspar: $(Na,K)AlSi_3O_8;SiO_2$	40%
Spodumene: $LiAlSi_2O_6$	40%
Olivine: $(Mg,Fe)_2SiO_4$	10%
Ilmenite: $FeTiO_3$	10%

Reade Advanced Materials ~ 300 mesh sieved
Further sieved to 50-75 μm size range

- Important for H_2 Reduction to increase efficiency

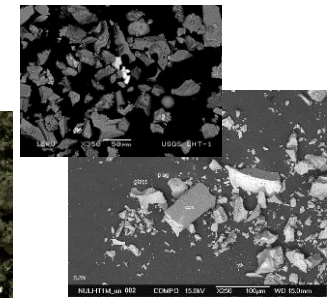
Lunar Simulant Development



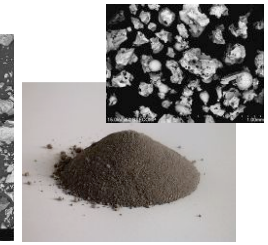


Glass Agglutinate-from LHT (USGS)

OB1 Highland Simulant (NORCAT/UNB)



Lunar Highland (LHT) Simulant (MSFC-USGS)

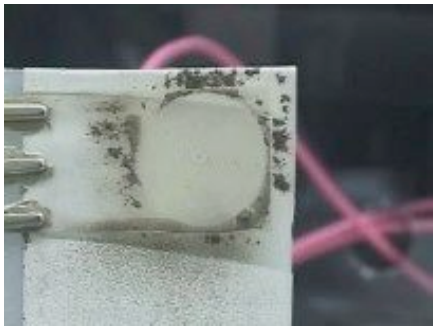


JSC1a (ORBITEC)

Regolith Mitigation

- Transparent electrodes on glass with lunar simulant; Raman spectrum not attenuated negatively
- Integration of electrode/window into Metering Device/Crusher for RESOLVE EBU#2 now in work

Before activation

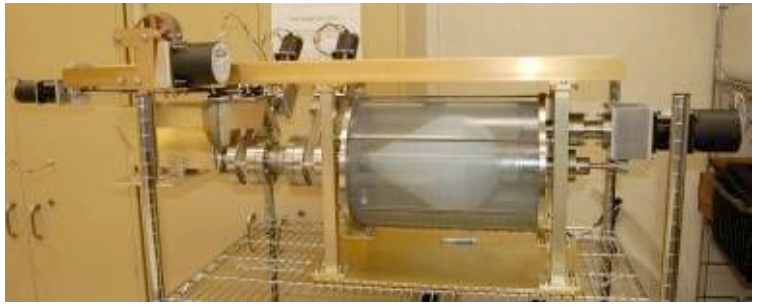


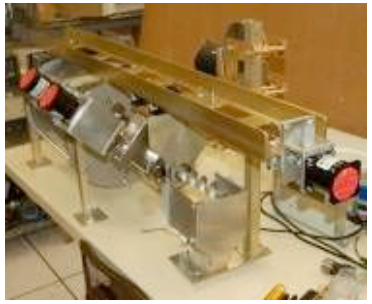
After activation

ISRU O_2 Extraction from Regolith Development

H_2 Reduction Rotating Reactor System (PILOT-LMA)

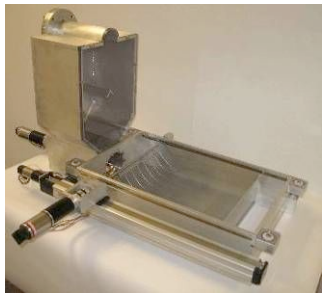
PILOT Hydrogen Reduction Kinetic Reactor





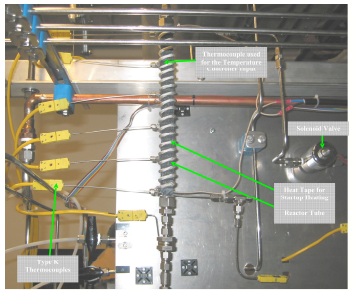
Reactor-Regolith Handling/Transport Testbed

CH_4 Carbothermal Reduction Reactor System (PILOT-ORBITEC)



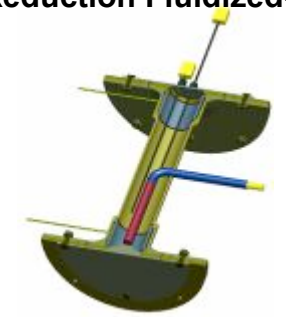
Regolith Handling/Transport Testbed

PILOT Carbothermal Reactor Testbed



Methane Regeneration Reactor

H_2 Reduction Fluidized-Bed Reactor System (ROE & ROxygen - NASA)



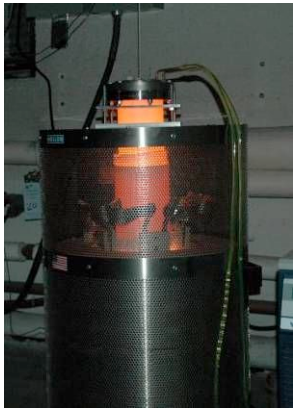
Hydrogen Reduction Fluidized Subscale Reactor Testbed

Water Electrolysis Breadboard

ISRU O_2 Extraction from Regolith Development (Cont.)

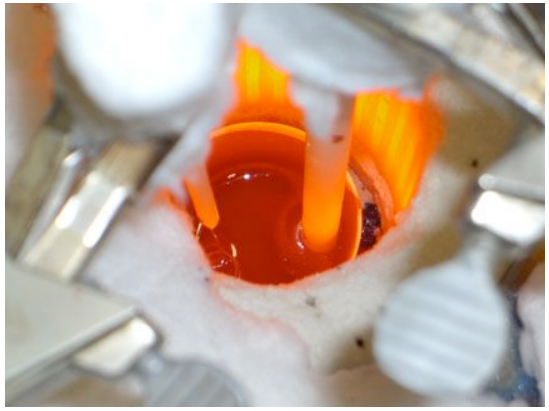
Regolith Salt & Molten Electrolysis

Ilmenox (FFC Process) Cell at FIT

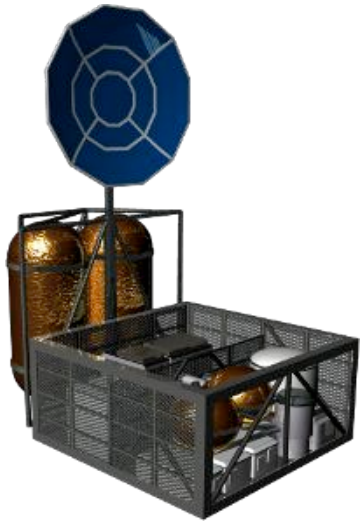


Molten Electrolysis Cell at MIT

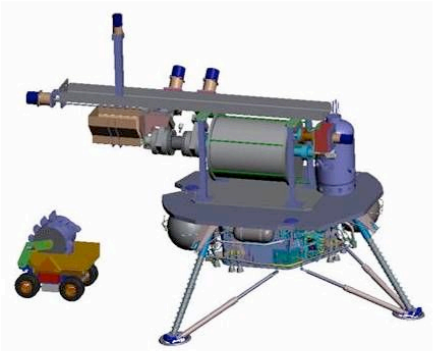
Low-Temperature Electrolysis Cell at KSC



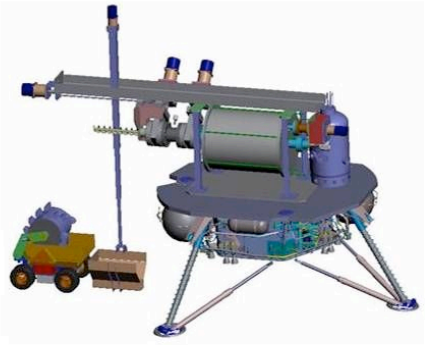
Early Electrolysis Cell Test at MSFC



Outpost O_2 Extraction Plant Concept with Solar Concentrator & O_2 Storage



Fully raised position



Fully lowered position

Robotic Precursor O_2 Extraction Plant Concept with Micro Excavator (LMA)

Robotic Precursor O_2 Extraction Subscale Demo

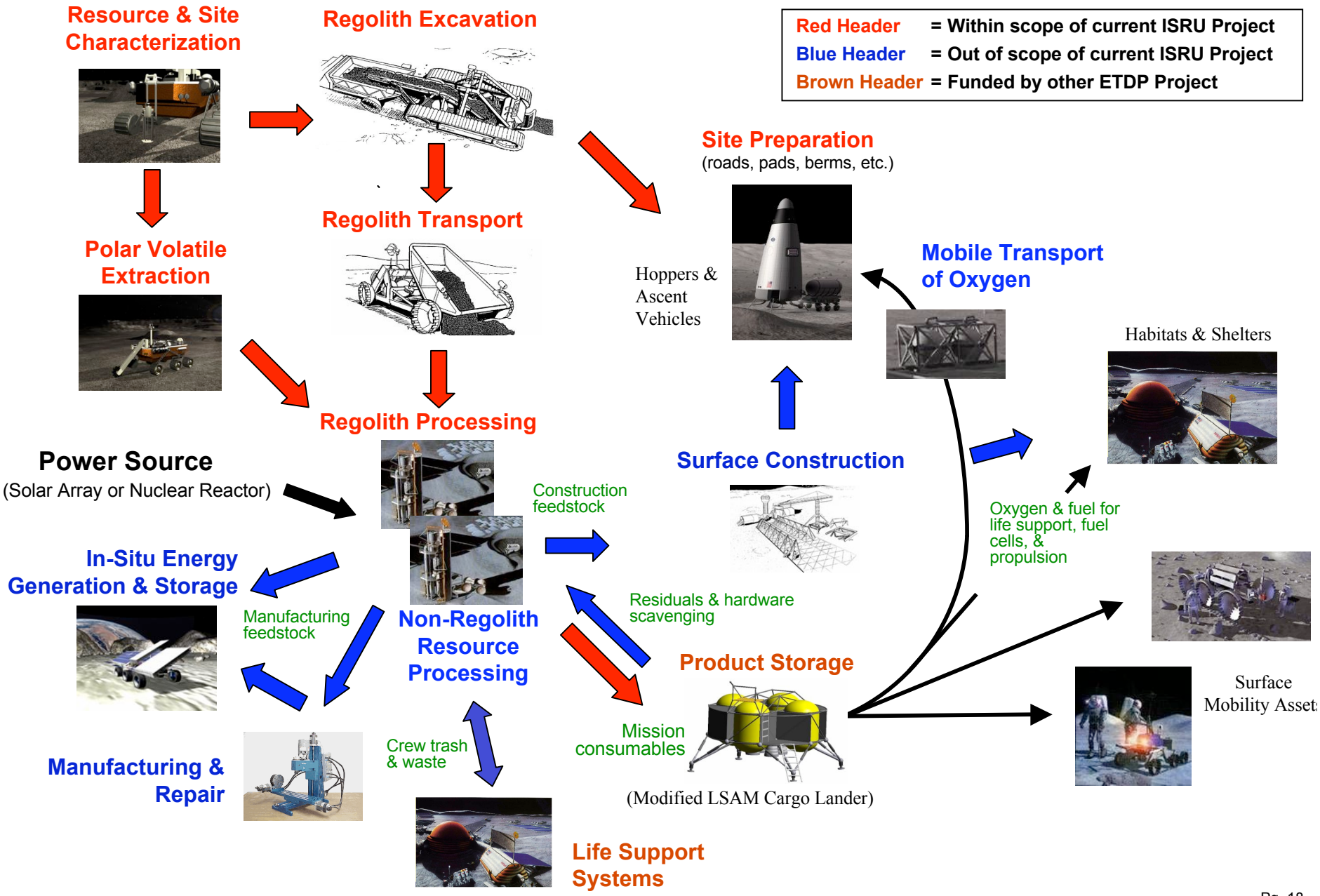
ISRU Technology and System Needs for Lunar Outpost

- **Excavation and Material Transport**
  - End-effectors for excavation, material transport, and surface manipulation for large and small surface mobility platforms
  - Dust insensitive mechanisms
  - Understanding of lunar regolith characteristics and behavior in 1/6-g
  - Comparative testing of concepts anchored to lunar regolith characteristics

- **Oxygen Production**
  - Oxygen extraction from regolith processing (low risk/low efficiency to high risk/high efficiency)
  - Solar concentrators and regolith thermal management
  - Dust insensitive sealing
  - Water, carbon dioxide, and gas processing and separation subsystems
  - Resource location and ‘mine’ planning for process control vs resource obtained

- **Methane Production**
  - High temperature pyrolysis
  - Solar concentrators
  - Water, carbon dioxide, and gas processing and separation subsystems
  - Bio-processing of regolith and trash

ISRU - Related Surface Elements & Activities



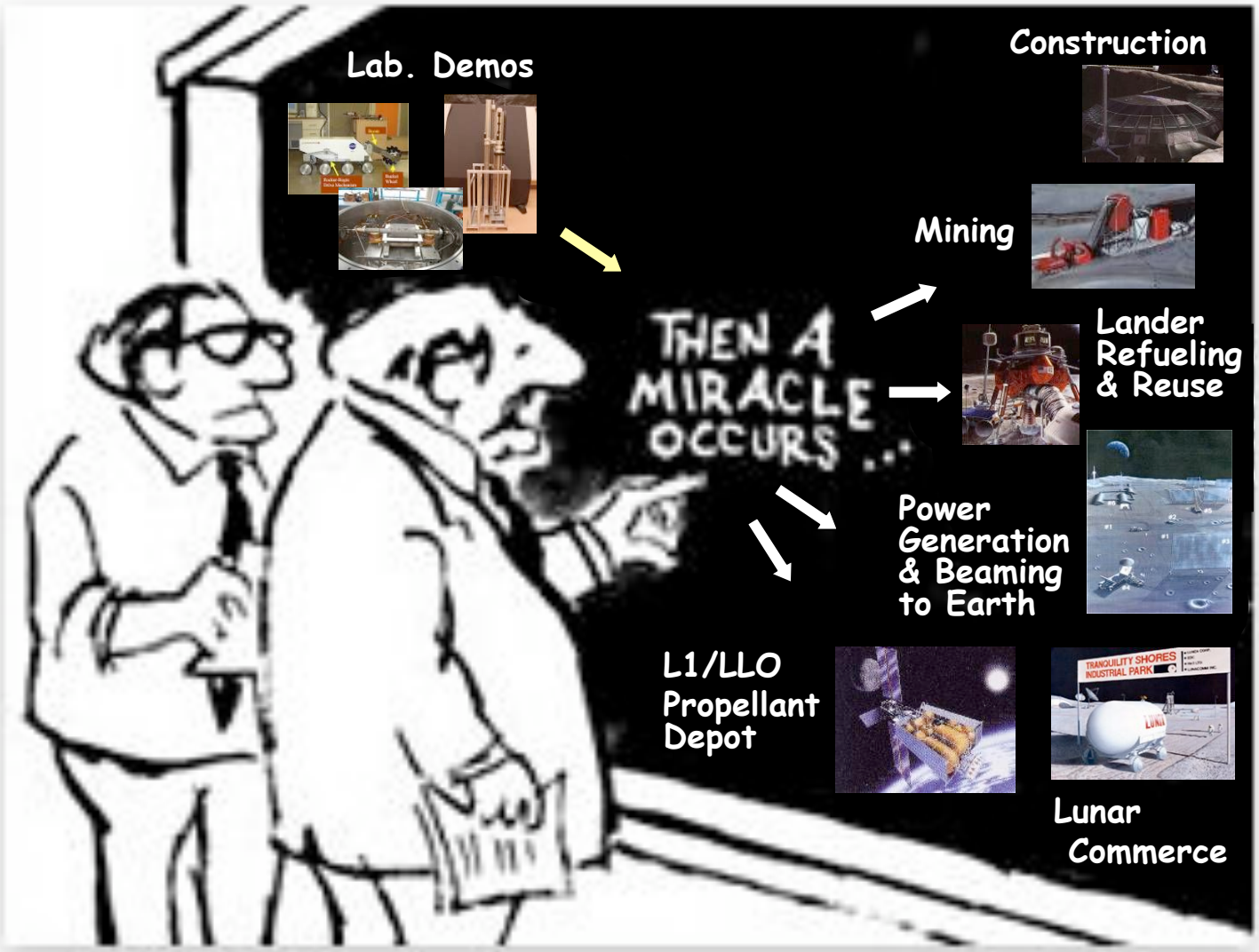
Technology and System Needs Linked to ISRU

- **Surface Mobility**
  - Large and small platforms for technology/concept and operation evaluation
- **Power**
  - High-cycle life, high-power density power systems for mobility platforms
  - Evaluation of common water electrolysis and O_2 storage/transfer with ISRU & Environmental Control & Life Support Systems (ECLSS)
  - Evaluation of common solar concentrator for ISRU and power generation
  - Evaluate common O_2, H_2, and water disconnects
- **Cryogenic Fluid Management**
  - Oxygen (and possibly methane) liquefaction and storage
  - Oxygen disconnects
  - Hydrogen (H_2) scavenging with ISRU
- **Autonomous Control and Failure Recovery**
  - Navigation and control software for long-term simplistic operation of excavation for O_2 production
  - Navigation and control for more complex operations: area clear w/ berm building, nuclear reactor burial, etc.
  - Oxygen production plant automation and control
  - Reliable instrumentation and fault control logic

Technology and System Needs Linked to ISRU (Cont.)

- **Thermal Management**
  - Oxygen production plant thermal management and rejection (KWs)
  - Regolith heat recovery
- **Life Support and EVA Suits**
  - Evaluation of common Water, carbon dioxide, and gas processing and separation subsystems
  - Evaluation of common storage/transfer with ISRU & Power
  - Evaluate common O_2, H_2, and water disconnects
  - Evaluation of EVA suit cooling with ISRU capabilities/consumables (moon and Mars)

Previous ISRU Development & Implementation Roadmap

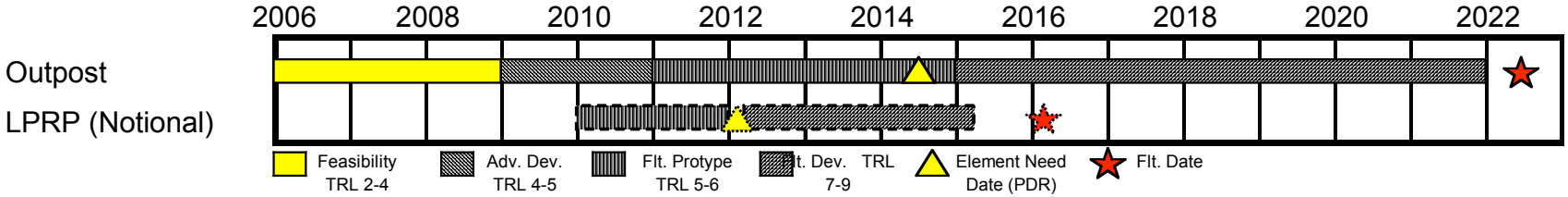


"I think more work is needed in this step."

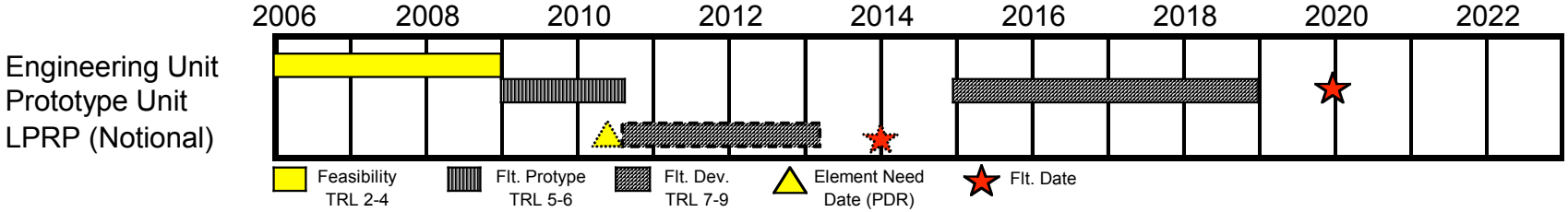
ISRU Development & Integration Strategy

- **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



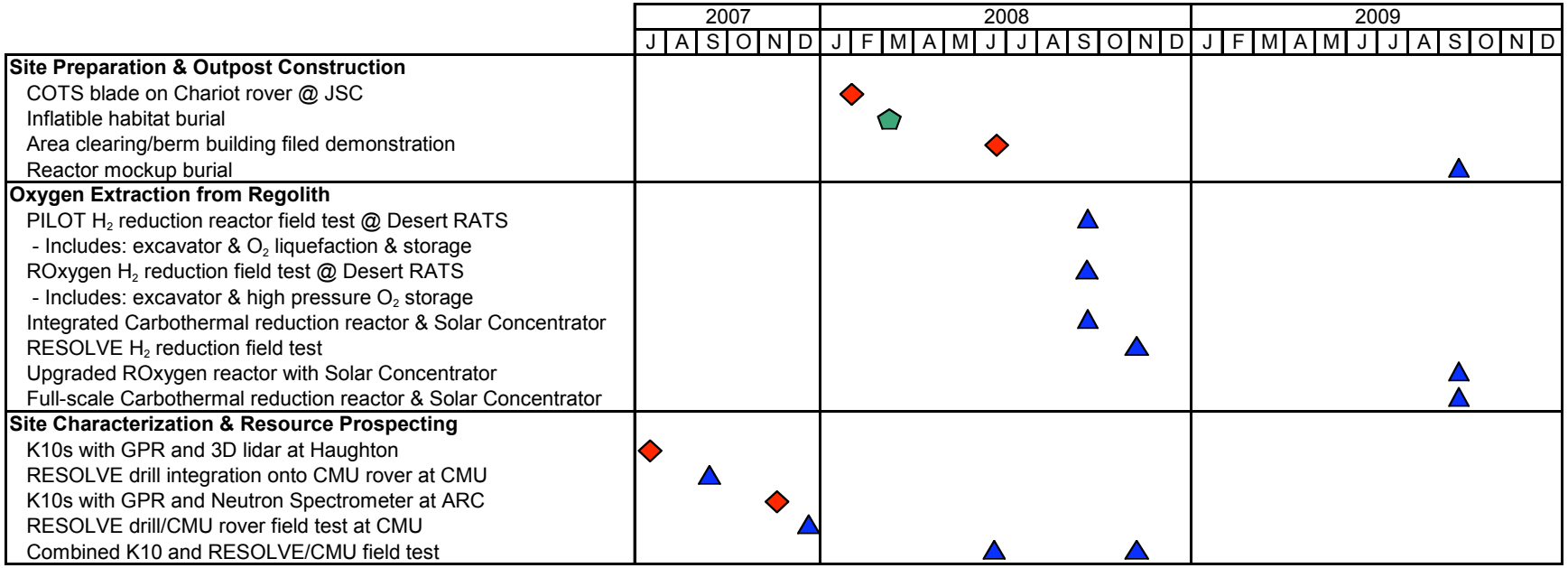
ISRU Precursor Demonstration (O_2 Production and Resource/Site Characterization)



Integrated Capability and Analog Site Demonstrations

Utilize laboratory and analog site demonstrations to:

- Demonstrate needed capabilities and operations for Lunar Outpost and technology/system 'customers'
- Demonstrate evolution and incremental growth in technologies and systems for Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness).
- Unite separate technology development efforts within NASA
- Develop partnerships and relationships across NASA and other US government agencies, and with International Partners, Industry, and Academia



▲ = In-Situ Resource Utilization (ISRU)-led Demo ◆ = Human-Robotic Systems (HRS)-led Demo ⬟ = Structures & Mechanics-led Demo

ISRU System & Surface Operations Ground Demo Plan

2007 | 2008 | 2009 | 2010 | 2011

Site Preparation & Outpost Deployment

Inflatable Shelter concept

(At JSC)

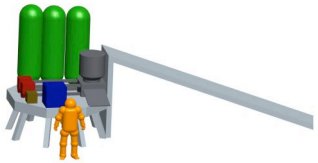
Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation

Perform area clearing and berm building with Chassis C & ISRU Blade

(At JSC & Hawaii)

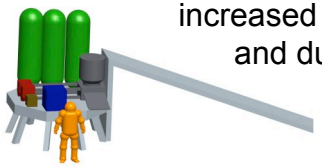
Add Autonomy & increased capabilities (ex. dig hole for reactor)

Oxygen Extraction from Regolith



Excavation and oxygen production from regolith with H_2 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

(At Hawaii- permafrost)

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

Possible:

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

Existing and Potential Partnerships

- **Corporations: Lockheed Martin**
  - Possible joint ISRU/Surface Mobility demonstration of excavation unit in FY08
- **Other US Government Agencies: Department of Energy, Dept. of Defense**
  - Possible leveraging of work performed on alternative fuel production (such as ethane or ethylene for propulsion)
    - Pacific Northwest National Laboratory (PNNL)
  - Leverage existing work in molten electrolysis for titanium and aluminum extraction from ore
- **Canadian Space Agency**
  - Joint development of lunar/Mars drilling technology through RESOLVE project
    - Agreement: Each providing funding and understanding to minimize overlap
- **Japanese Aerospace and Exploration Agency (JAXA)**
  - Possible technology development and lunar simulant leveraging
  - Possible joint Lunar flight opportunities
- **European Space Agency (ESA)**
  - Possible technology development leveraging
  - Possible joint flight hardware and opportunities (lunar & Mars)

Possible Approaches for Partnerships with ISRU

A. Joint instrument/missions for:

- Resource mapping & characterization
- ISRU demonstrations for consumable production, energy production, habitat & surface construction

Ex. CSA drill on NASA lunar prospecting mission

B. Separate but coordinated missions and capabilities

- Different hardware to do same capability but shared lessons learned (ex. different oxygen extraction method from regolith)

C. Pre-agreed upon lead roles of strategic interest to each Partner

- Partners provide critical capability not provided by US

Ex. International Partner provides excavator/surface mobility platform to bring regolith to NASA oxygen extraction plant