Development and Demonstration of Sustainable Surface Infrastructure for Moon/Mars Missions

62nd International Astronautical Congress 2011

Cape Town, South Africa
Oct. 5, 2011

Gerald B. Sanders, NASA/Johnson Space Center
William E. Larson, NASA/Kennedy Space Center
Martin Picard, Canadian Space Agency

Problems with Technology and System Development for Exploration Architectures

- **Architectures tend to focus on minimizing upfront costs and mass with little/no assessment of life cycle costs or long-term sustainment**
  - Reusability of transportation elements is not considered;
  - Existing or low risk technologies utilized instead of higher payoff options with higher initial costs
  - ➢ Impact: Long-term affordability and sustainability of the program is reduced
- **Design & development of subsystems have little/no interaction with other subsystems or with the same subsystem in other Vehicles or Elements**
  - Life support, power, thermal control and propulsion all utilize different hardware and fluids
  - Major subsystems are customized for each Element or Vehicle
  - ➢ Impacts: No commonality of hardware or integration of fluids and increased costs
- **Optimization and selection of technologies is not adequately coordinated at the architecture level**
  - Introduction of ISRU changes need/focus of air/water/trash recycling technologies
  - Different approaches and selections of fluids/consumables across subsystems
  - Technologies and hardware developed by International Partners not considered
  - ➢ Impacts: Competing technologies, minimized performance from Vehicle/Element perspective and wasted resources

What is need is a more Integrated, Sustainable, & Evolvable Approach to Exploration

Goal: Use Early, Use Often, Use for Multiple Destinations, Be Evolvable

- **Modular Systems – Common Technologies**
  - Lower development costs & logistics
  - Redundancy
  - Flexibility & evolution/growth

- **Common Fluids**
  - Integrate across multiple systems
  - Common regeneration and production techniques
  - Standards and common interfaces
  - Mission flexibility in use & failure recovery
  - ➢ Water, Oxygen-Hydrogen and/or Oxygen-Methane

- **Optimize Across Multiple Vehicles and Elements**
  - Consider design implications/requirements for Moon, Mars, and NEOs
  - Standardize fluid quality & pressure for ISRU, power, propulsion, & EVA
  - Common hardware and operations

- **Enhanced Transportation/Mobility**
  - Reusable and expandable transportation and depot elements
  - Extensive surface access

- **In-Situ Resource Utilization (ISRU) – Changes Paradigm of Exploration**
  - ***Make it vs Bring it*** from Earth
  - Identify and use ISRU solve architecture problems: risk, mass, logistics
  - Make technology selection and design choices on:
    - Return-on-Investment & Life Cycle Evaluation of all exploration systems
    - Long-term goals vs near-term costs and objectives (ie. "Boots on Moon")

Make It vs Bring It – A New Approach to Exploration

Reduces Risk
- Minimizes/eliminates life support consumable delivery from Earth – Eliminates cargo delivery failure issues & functional backup to life support system
- Increases crew radiation protection over Earth delivered options – In-situ water and/or regolith
- Can minimize impact of shortfalls in other system performance – Launch vehicles, landers, & life support
- Minimizes/eliminates ascent propellant boiloff leakage issues – In-situ refueling
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction

Increases Performance
- Longer stays, increased EVA, or increased crew over baseline with ISRU consumables
- Increased payload-to-orbit or delta-V for faster rendezvous with fueling of ascent vehicle
- Increased and more efficient surface nighttime and mobile fuel cell power architecture with ISRU
- Decreased logistics and spares brought from Earth

Increases Science
- Greater surface and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU excavation and trenching capabilities
- Increased science payload per mission by eliminating consumable delivery

Increases Sustainability/Decreases Life Cycle Costs
- Potential reuse of landers with in-situ propellants can provide significant cost savings
- Enables in-situ growth capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Supports Multiple Destinations
- Surface soil processing operations associated with ISRU applicable to Moon and Mars
- ISRU subsystems and technologies are applicable to multiple destinations and other applications
- Resource assessment for water/ice and minerals common to Moon, Mars, and NEOs

What is 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: atmosphere, regolith, volatiles/water, sunlight, cold traps, vacuum
- Discarded Materials: trash/waste, residual propellants, descent stages, etc.

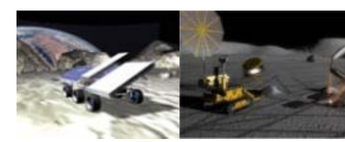
Five Major Areas of ISRU

- **Resource Characterization and Mapping**
  Determine physical, mineral/chemical, and volatile/water

- **Mission Consumable Production**
  Make propellants, life support gases, fuel cell reactants, etc.

- **Civil Engineering & Surface Construction**
  Make radiation shields, landing pads, roads, habitats, etc.

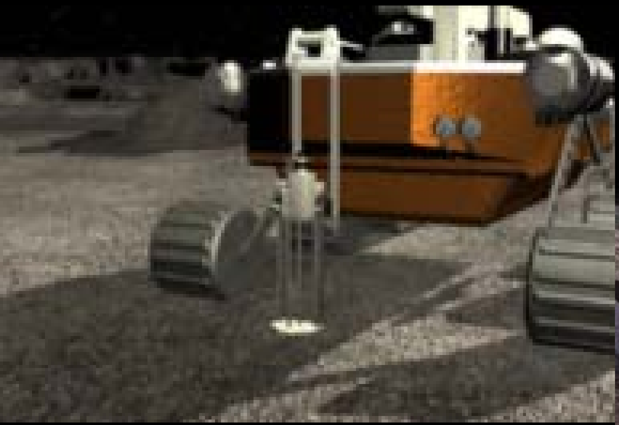
- **Energy Generation, Storage & Transfer w/ In-situ Resources**
  Solar, electrical, thermal, chemical based systems



- **Manufacturing & Repair w/ In-situ Resources**
  Make spare parts, wires, trusses, integrated structures, etc.

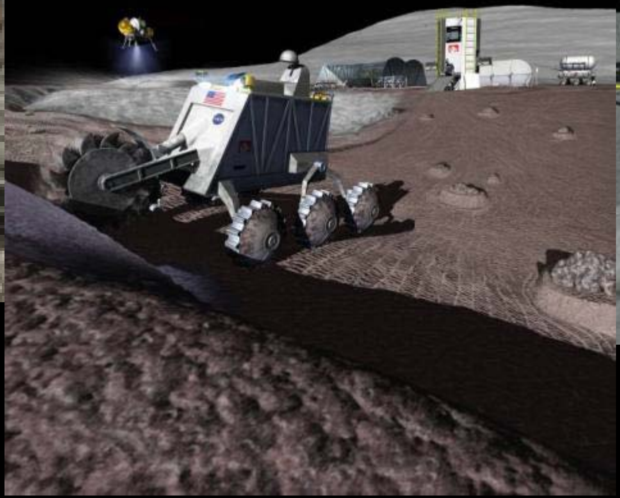
- **'ISRU' is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.

Lunar ISRU Mission Capability Concepts

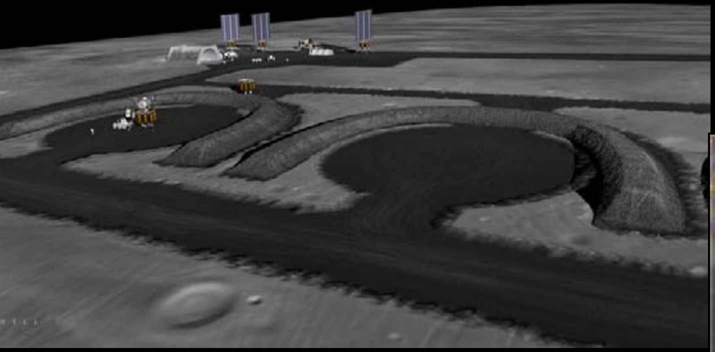


Resource Prospecting – Looking for Polar Ice

Excavation & Regolith Processing for O_2 Production

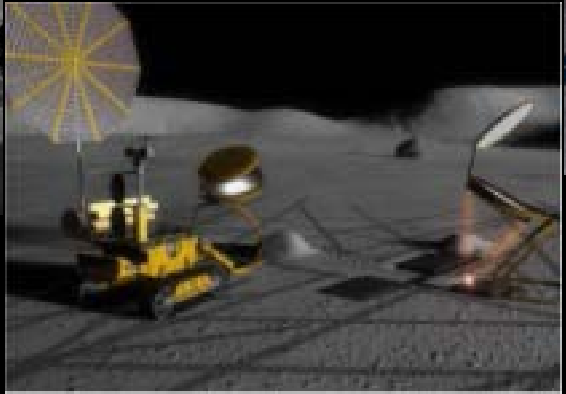


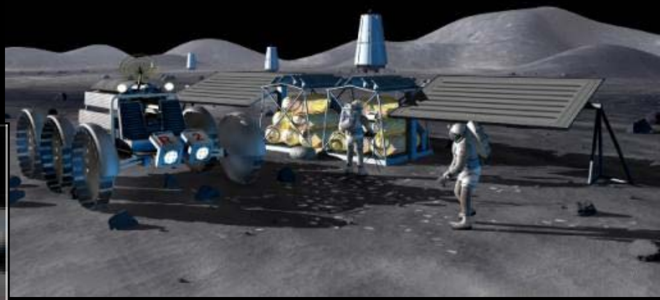
Carbothermal Processing with Altair Lander Assets



Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





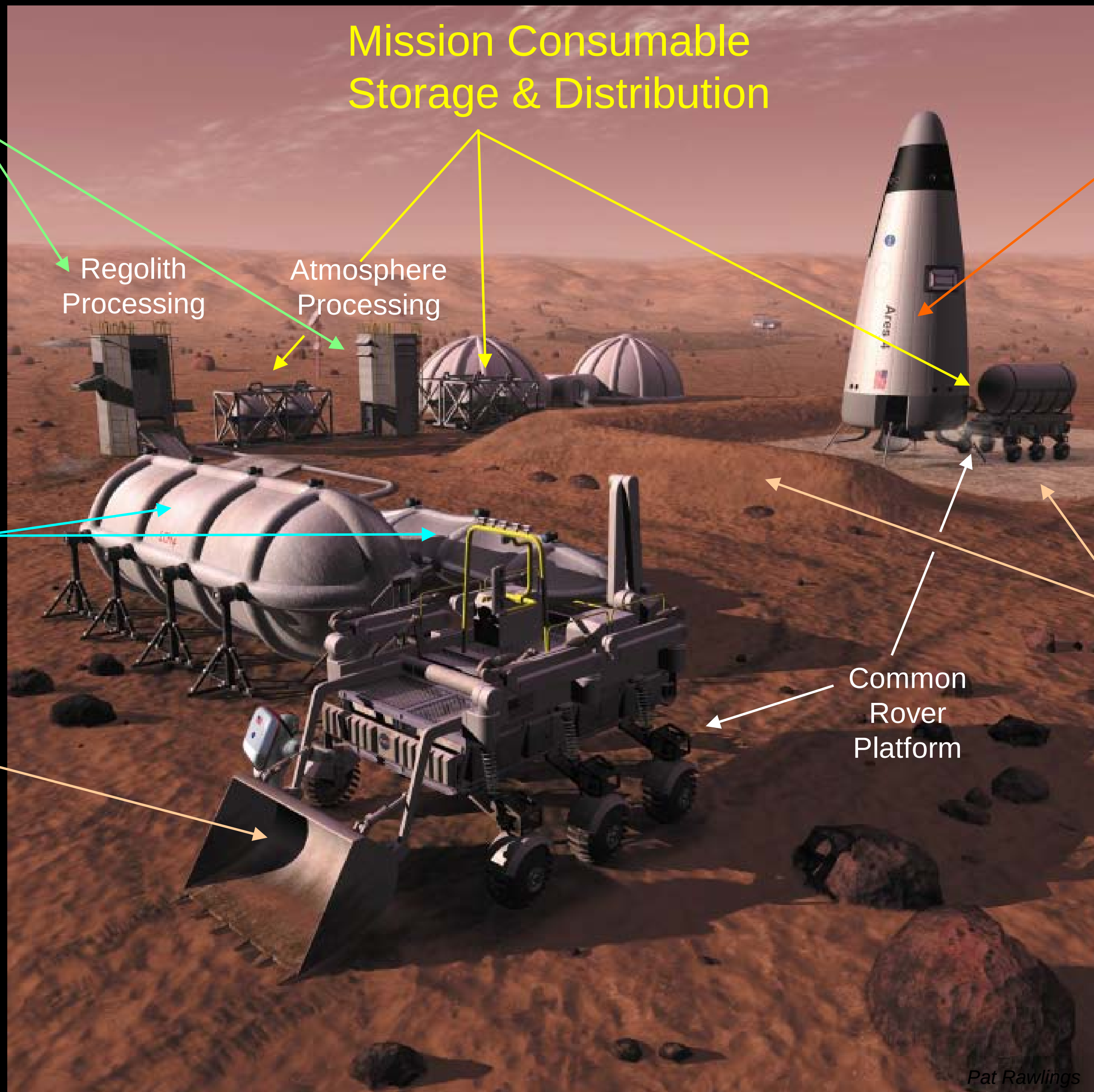
Consumable Depots for Crew & Power

Mars ISRU Mission Capability Concepts

Resource Processing Plants

Collapsible/ Inflatable Cryogenic Tanks

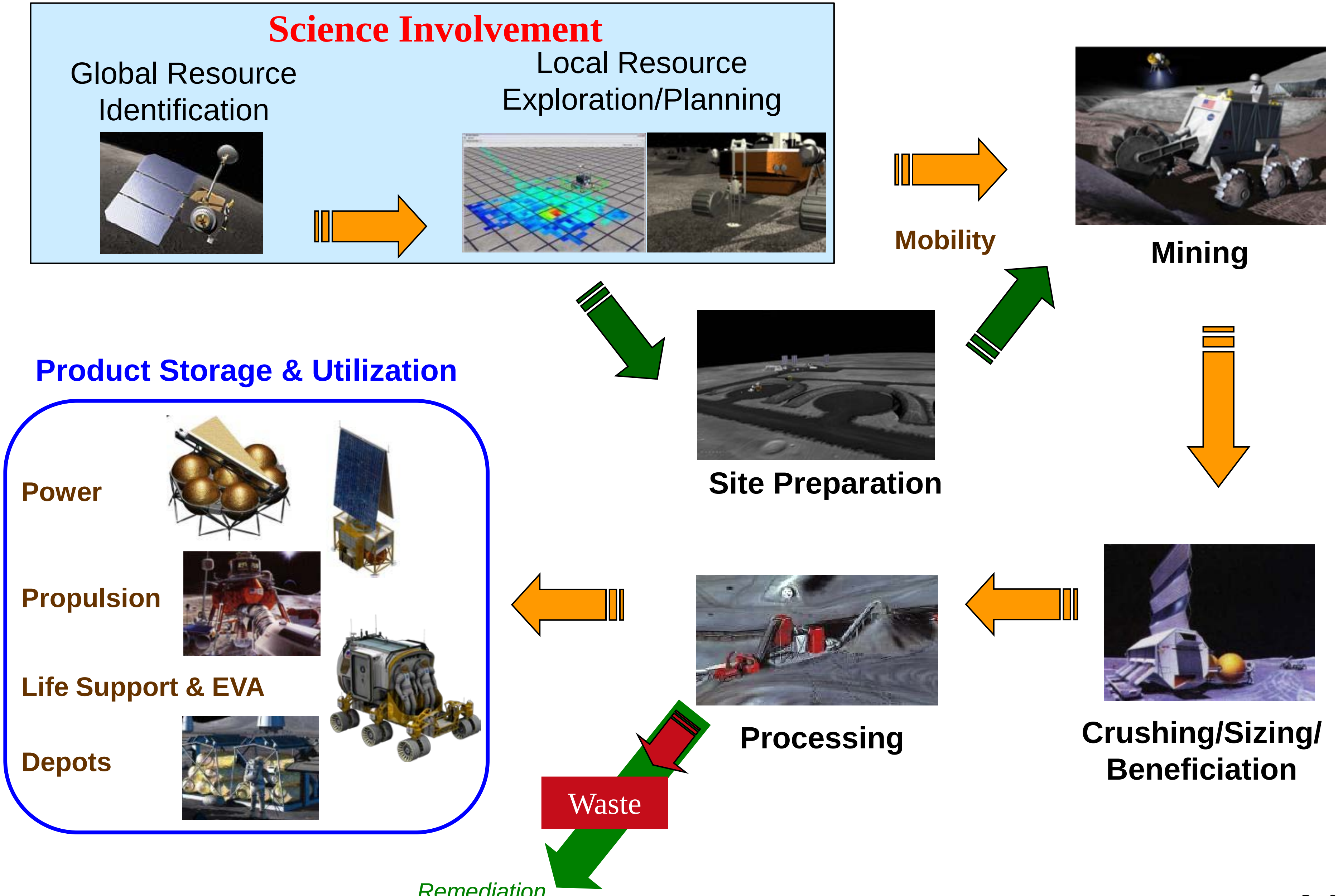
Multi-use Construction/ Excavator: resources, berms, nuclear power plant placement, etc.



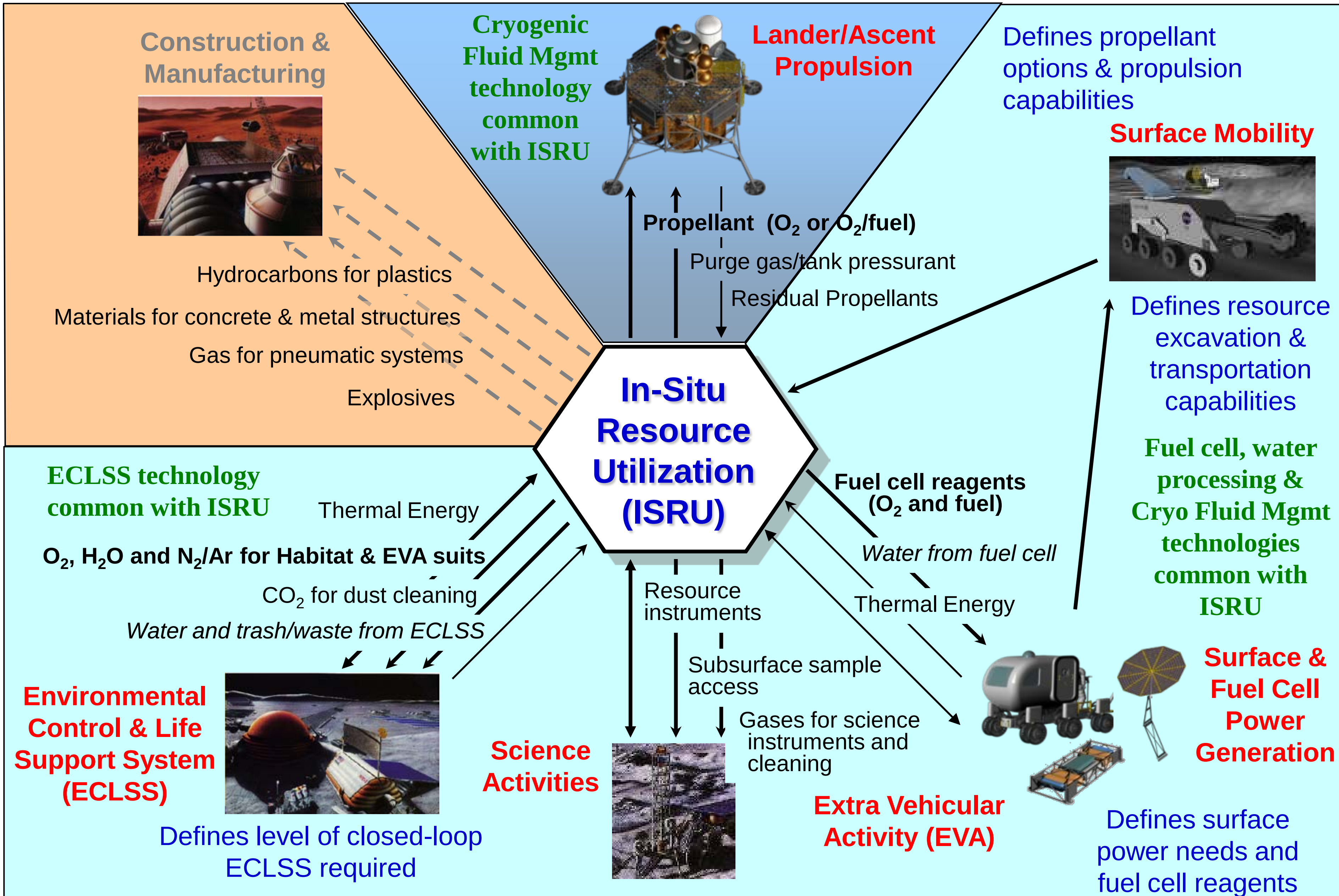
Reusable lander/ascent vehicle or surface hopper fueled with in-situ propellants

Landing pad & plume exhaust berm

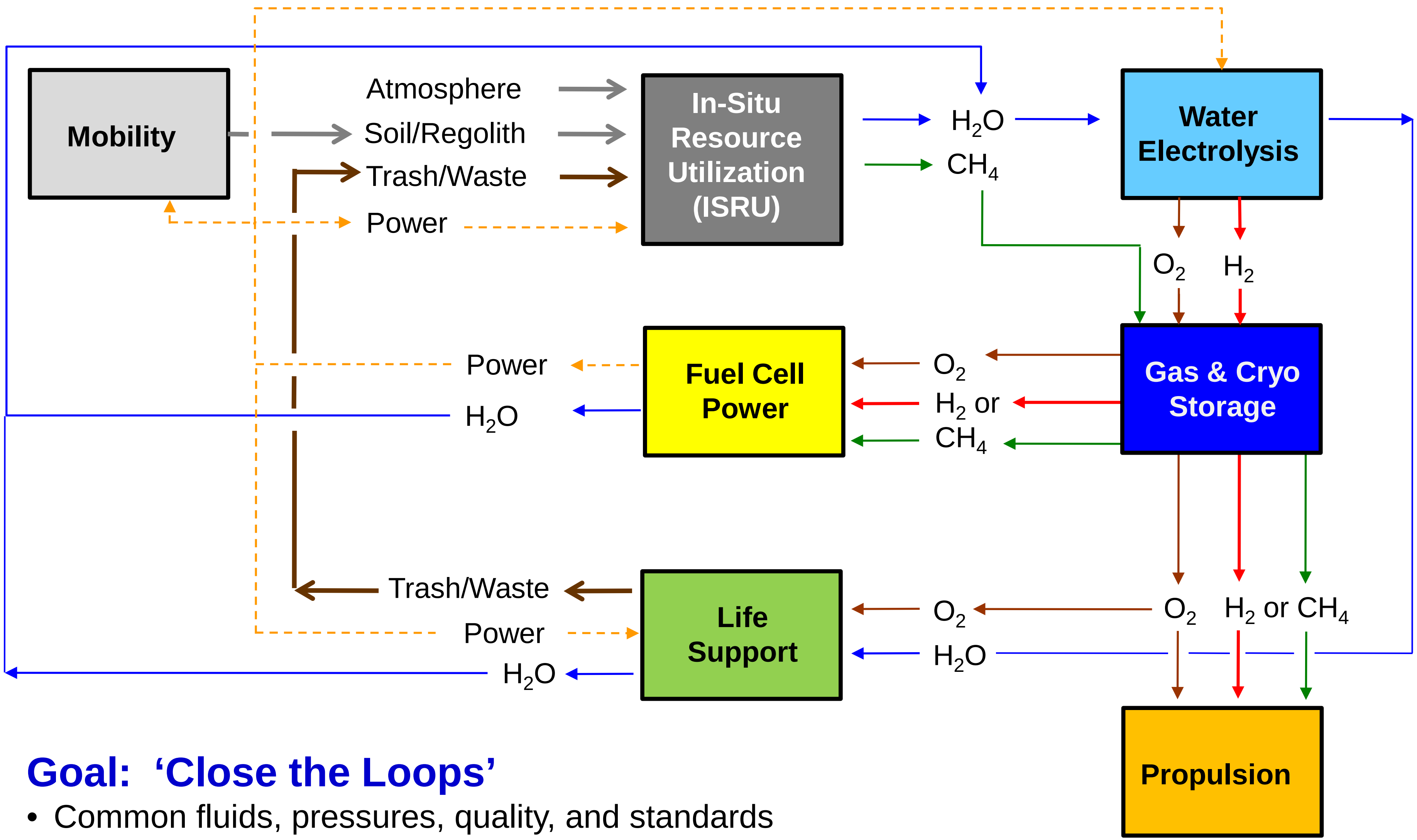
ISRU Development and Testing Focus: Space ‘Mining’ Cycle



ISRU Connectivity with Other Exploration Elements Strongly Influences Designs and Architecture



Integrated ISRU – Power – Propulsion – Life Support Cycles



Goal: 'Close the Loops'

- Common fluids, pressures, quality, and standards
- Common storage, distribution, and interfaces
- Common technologies and hardware for flexibility and reduced DDT&E

Development and Integration Strategy

- **Need Early, Achievable, & Visible milestones & successes;** Utilize Laboratory and Analog Site Demonstrations to:
  - Demonstrate capabilities and operations
  - Demonstrate incremental growth in technologies and systems
  - Engage architect/mission planners and public

- **Take evolutionary approach in development;** Phases of 1-3 years each
  - Phase I: Demonstrate Feasibility
  - Phase II: Technology and systems evolution optimized vs key performance parameters
  - Phase III: Modify and test for mission environment applicability
  - Phase IV: Reach TRL 6 for insertion into flight missions

- **Coordinate development across all Surface/Transportation Elements**
  - Identify common requirements, processes, hardware, and operations
  - Coordinate development of hardware to align project schedule
  - Demonstrate interfaces and interconnection of hardware and operations

- **Partner and leverage existing hardware & technology development activities**
  - Develop partnerships and relationships across NASA and other US government agencies, and with International Partners, Industry, and Academia
  - Perform joint hardware and operation tests with other Projects and Elements
  - Link multiple technology development activities (AES, OCT, SBIR, CIF/CDDF, IR&D, etc.)

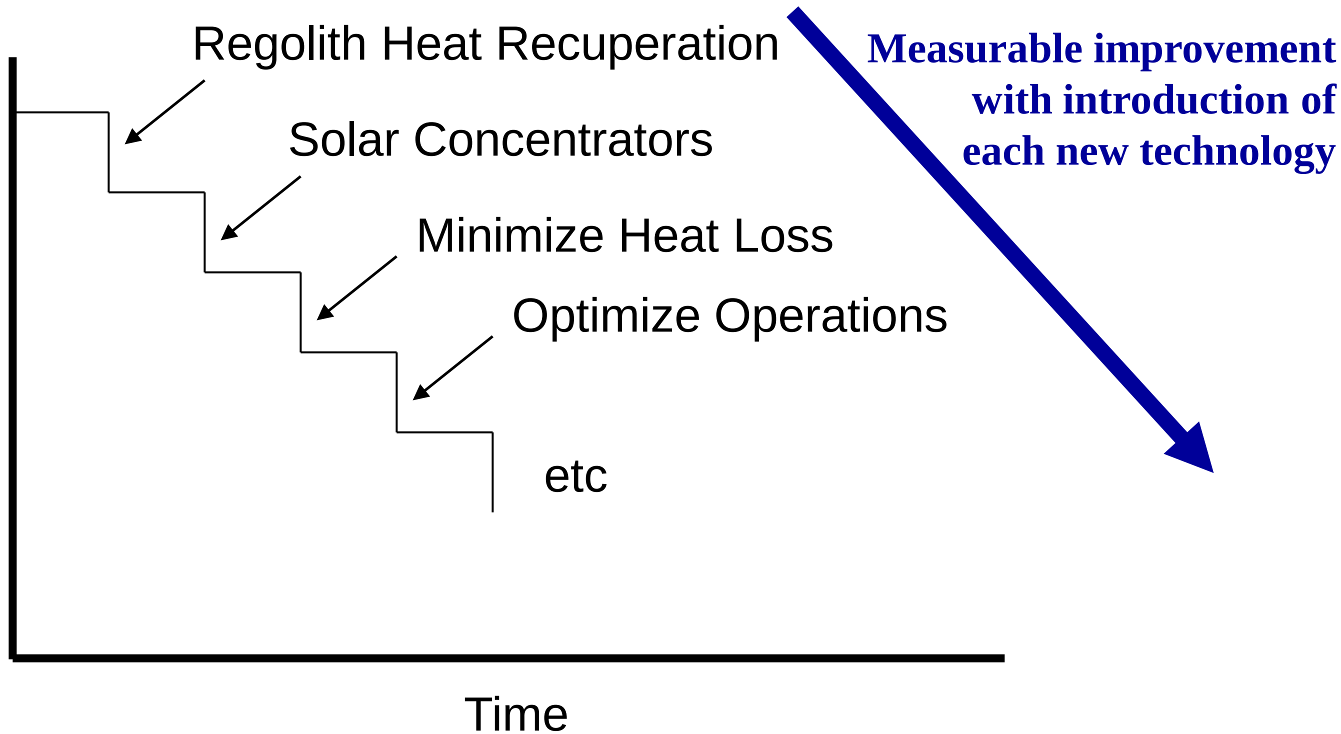
Evolutionary Approach for Technology, Module, & System Development

Technology development philosophy

- **Build a little, test a lot, modify to improve performance, repeat**

Key Performance Parameters (KPPs):

- *System mass per kg oxygen produced*
- *System energy per kg oxygen produced*
- *Difference between system and architecture*



Module development philosophy

- **Develop for multiple applications**
- **Upgrade and incorporate as new modules become available**

Why Perform Analog Field Testing for Science, Exploration & ISRU?

Key Programmatic Analogue Field Test Purpose

- **Expand NASA and CSA partnership; Include other International Partners in analogues**
- **Expand integration of Science & Engineering for exploration, particularly with ISRU**
- **Link separate technology and system development activities**
- Develop and enhance remote operations and mission concepts; introduce new technologies
- Evaluate parallel paths and competing concepts
- Be synergistic with other analogue test activities (past and future)
- **Public Outreach, Education, and "Participatory Exploration"**

Key Technical Analogue Field Test Purpose

- **Stress hardware under realistic environmental and mission operation conditions to improve path to flight**
- Improve remote operations & control of hardware for surface exploration and science
- Promote the testing of multiple surface and transportation systems to better understand integration and operation benefits and issues
- Promote use of common software, interfaces, & standards for control and operation (ISECG)
- Focus on interfaces, standards, and requirements (ISECG)
- Focus on modularity and 'plug n play' integration (ISECG)

Intrinsic Benefits of Field/Analog Testing

- Develop Scientists, Engineers, and Project Managers for future flight activities
- Develop International Partnerships
- Develop Teams and Trust Early
- Develop Data Exchange & Interactions with International Partners (ITAR)

ISRU-Surface Operations Analog Test Focus

ISRU Objectives – Space ISRU Mining Cycle

- Demonstrate mobile resource characterization (physical, mineral, and volatile) capabilities for lunar polar missions
- Demonstrate technologies and end-to-end system operations for mission critical consumable production on Moon, Mars, & NEO's (oxygen, water, fuel)
- Demonstrate civil engineering and site preparation capabilities that might be required for future human missions (landing pads, roads, protection, etc.)

Surface Operations and ISRU Interface/Interaction Objectives

- Link science operations and instrumentation with site characterization & resource prospecting/mapping needs
- Link ISRU needs and products with Power, Propulsion, and Life Support consumable needs and waste
- Assess interfaces and common hardware potential with Power, Propulsion, and Life Support system developers
- Coordinate ISRU development and system integration with International Space Agencies in mission critical roles

1st ISRU - Surface Operations Analog Field Test

Field Dates: Oct. 30 to Nov. 15, 2008 **Location: Mauna Kea , Hawaii**

Field Test Objectives

1. **Mobile Resource Characterization & Oxygen Demonstration (RESOLVE/Scarab)**
   - Demonstrate resource prospecting, site surveying, and oxygen production
   - Demonstrate hardware integration and mobile surface operations
   - Opportunistic Demos: Hand-held Raman spectrometer (CSA); Mossbauer spectrometer (JSC) on Cratos rover; CHEMIN XRD/XRF (ARC/LANL)
2. **OPTIMA (ISRU End-to End Outpost Scale Oxygen Production & Storage Field Test)**
   - Demonstrate excavation and regolith delivery to ISRU plant
   - Demonstrate oxygen extraction from regolith at outpost production rate
   - Demonstrate system integration, modularity of modules for swapping, and surface operations
3. **Demonstrate partnership with International Space Agencies (CSA and DLR) and State of Hawaii and Pacific International Space Center for Exploration Systems (PISCES)**

5 NASA Centers, 2 International Space Agencies, 7 Companies, & 2 Universities

Customers

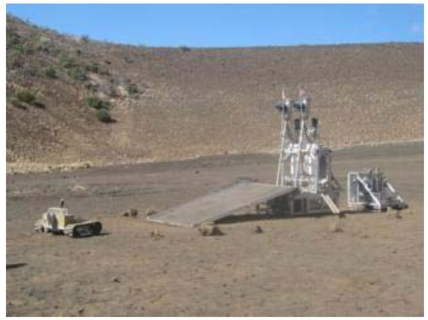
- CxPO Lunar Surface Systems Office
- SMD, OSEWG, and ESMD Lunar Scientist
- NASA ESMD Advanced Capabilities & Directorate Integration Office
- NASA Office of External Relations

ISRU Hardware Tested at 2008 Analog Site

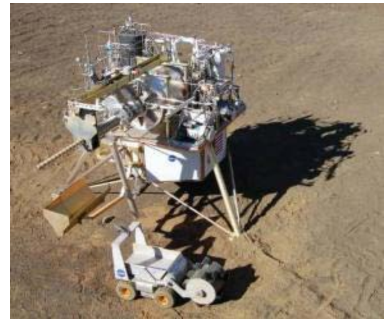
Lunar Prospecting

- Scarab Rover
- RESOLVE
- TriDAR Vision System
- Tweels

Outpost-Scale O_2 from Regolith

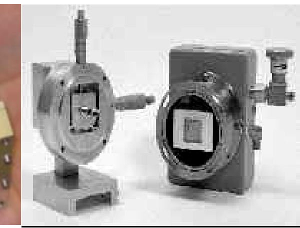


- ROxygen H_2 Reduction
- Water Electrolysis
- Cratos Excavator



- PILOT H_2 Reduction
- Water Electrolysis
- Bucketdrum Excavator

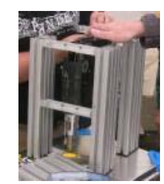
Process Control & Science



- Moessbauer spectrometer
- Mini Chemin XRD/XRF

- **Canadian Space Agency**
  - TriDAR imager, Satellite communications, remote operation of Drill and TriDAR navigation, and on-site personnel and payload mobility
  - NORCAT, Xiphos, Argo, Virgin Technologies, EVC, Ontario Drive Gear, **University of Toronto**

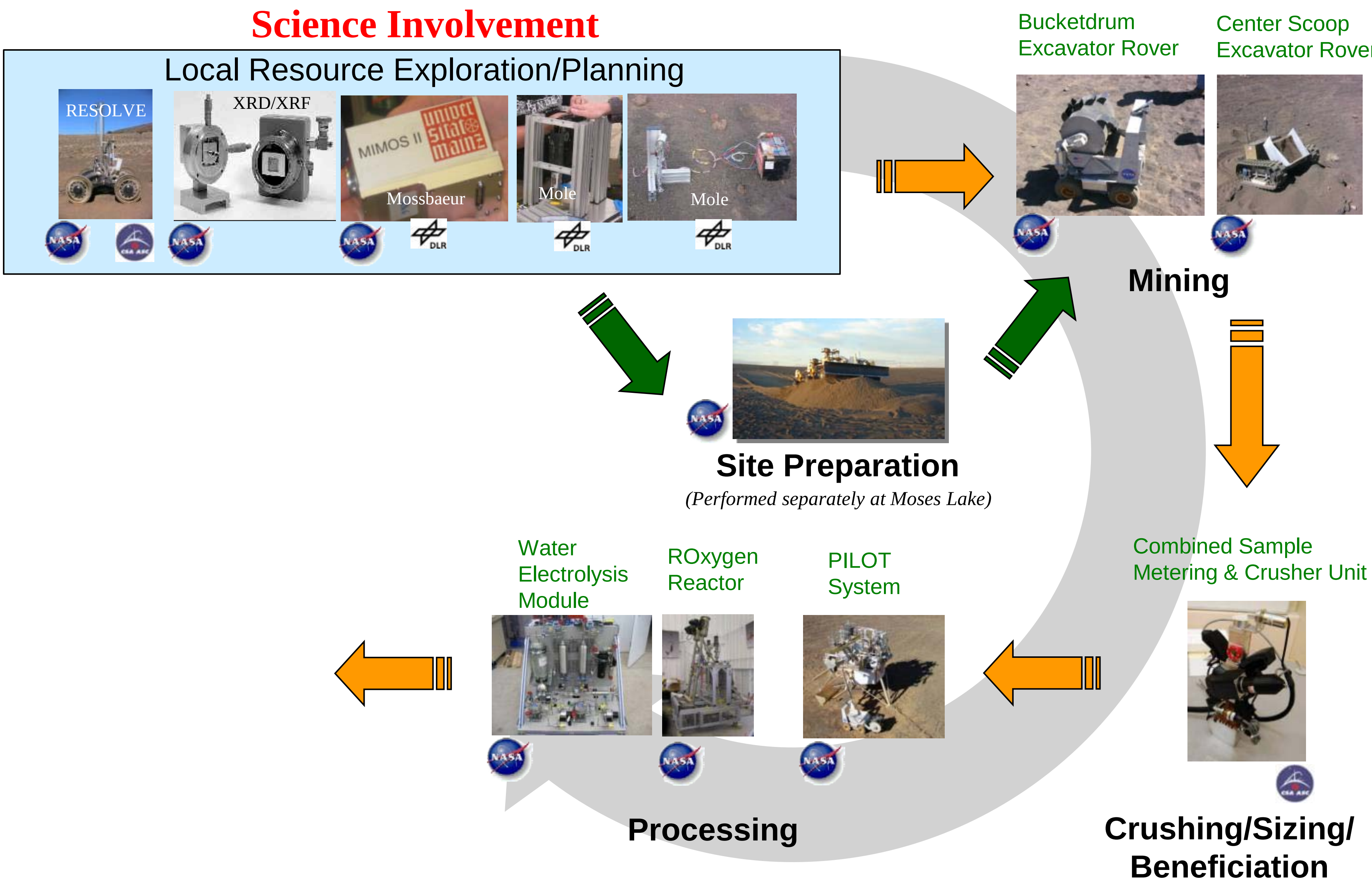
- **German Space Agency (DLR)**
  - Instrumented "Mole" & Sample Capture Mole
  - Moessbauer spectrometer



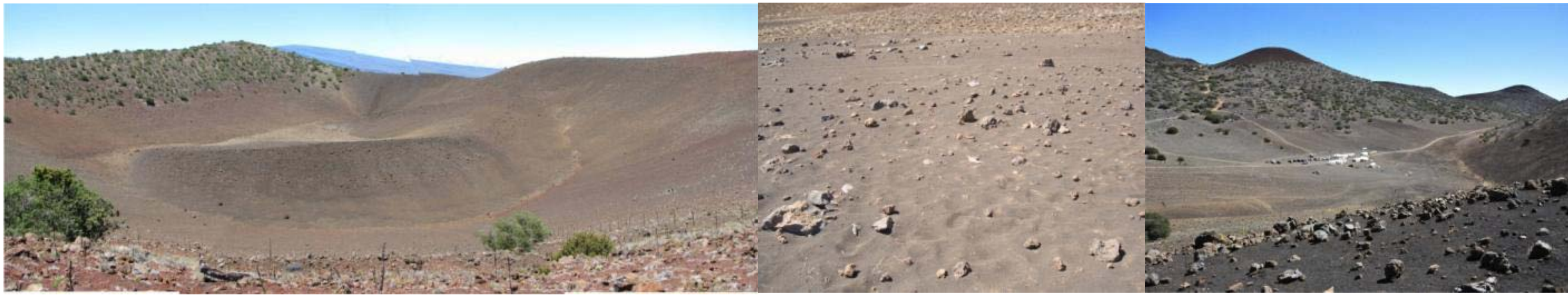
- **Carnegie Mellon University**
  - SCARAB Rover

- **JPL Partnership with Michelin on 'Tweels' testing**

1st Demonstration of Space Mining Cycle



2008 Analog Test Site; Mauna Kea, Hawaii



Analog Site Features

Toilets

Medical Supplies

Accessories

On-site Food & Drink

Wind and Dust

Mist & Light Rain

Magnetic Dust

Major Results From Nov. 2008 ISRU Analog Field Test

- ☑ Demonstrated end-to-end operation of RESOLVE/Scarab; roving over varied terrain, dark navigation, drill site selection; remote operation from CSA
- ☑ Demonstrated end-to-end PILOT & ROxygen operations: regolith delivery, reactor fill/empty, regolith processing, water capture and clean-up, oxygen production
- ☑ RESOLVE: 6 Drilling, 6 Volatile characterization; and 4 Oxygen extraction operations
- ☑ PILOT: 6 complete reactor operations; 1000 ml of water produced from iron-oxide
- ☑ ROxygen: 5 complete reactor operations (2 Argon/3 Hydrogen)
- ☑ 1st Successful field deployment of ISRU
- ☑ Field deployment with International Partners, Canadian Space Agency and German Space Agency
- ☑ 1st field deployment where site access, test infrastructure, food, and lodging were provided by a 3rd party; Pacific International Space Center for Exploration Systems (PISCES)

2nd ISRU - Surface Operations Field Test

- **Field Dates: Jan. 24 - Feb. 14, 2010 Location: Mauna Kea , Hawaii**

- **Field Test Purpose**
  - Advance ISRU hardware and system hardware over 1st analog field test; ISRU 'mining' cycle
  - Expand ISRU system/capability integration with other transportation and surface elements
  - Increase scope and criticality of international partner involvement in ISRU development

- **NASA Hardware-Operation Objectives**

1. **O_2 Production from Regolith**: Test enhanced Oxygen extraction from regolith system & operations
2. **ISRU Product Storage & Utilization**: Test hardware, operations, and energy systems that promote product usage
3. **Lunar ISRU, Exploration, & Science Integration**: Integrate lunar exploration, resource & site evaluation, and lunar science objectives, instruments, and operations
4. **Site Preparation**: Test hardware, operations, and surface sintering techniques
5. **Field Geology Training**: Train astronauts, ISRU, and NASA/CSA management on geology

8 System Modules – 7 Instruments

6 NASA Centers, 6 Small Businesses, 5 Universities

(42 people plus visitors)

12 System Modules & Attachments; Infrastructure

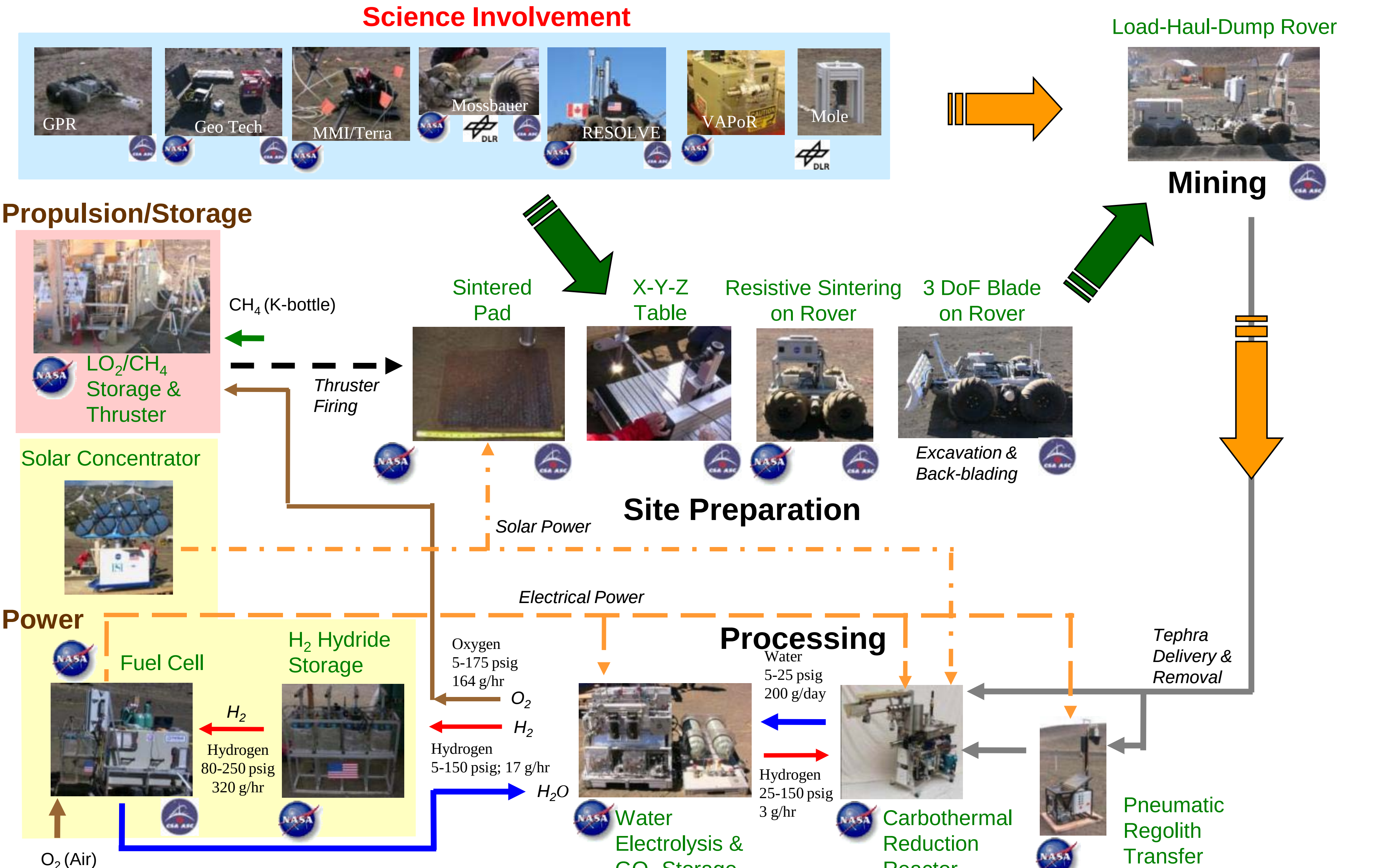
3 Canadian Government Agencies, 8 Small Businesses, 2 Universities

(46 people plus visitors)

Build Confidence: ISRU Analog Field Tests

2nd Test – Jan. 2010

Science – ISRU O_2 Production & Construction – Power – Propulsion/Cryo Fluid Mgmt



Major Results From 2nd ISRU – Surface Operations Analog Field Test

- **Dust to Thrust Successful:** Demonstrate hardware and operations in all steps in ISRU from finding resources to utilizing in power and propulsion applications
- **Integration of Surface/Transportation Elements Successful**: Integrate ISRU, Power, Fluid Management, and Propulsion modules to 'Close the Loop' for better understanding of interfaces and design impacts

- ☑ Extracted oxygen from local tephra (28 gms or 9.6% ave. yield) using advanced processing and regolith transfer hardware in end-to-end configuration
- ☑ Electrolyzed water from tephra and fuel cell, transferred oxygen to cryogenic cart for liquefaction, and performed 17 LO_2/CH_4 thruster firings; "Dust to Thrust"
- ☑ Sintered two surface pads with two different methods and performed thruster firings with high speed camera to understand plume effects on unmodified and modified surfaces
- ☑ Integrated NASA and CSA/Canadian hardware in multiple critical applications
- ☑ Operated RESOLVE remotely from KSC and Solar Collector, Carbothermal Reactor, and Water Electrolysis systems remotely from JSC
- ☑ Tested SMD FSAT and MMAMA instruments for site/mineral characterization and support oxygen extraction process evaluation
- ☑ Completed field geology training with NASA and CSA managers and a CSA astronaut

3rd ISRU – Surface Operations Field Test

Field Dates: June, 2012 **Location: Mauna Kea , Hawaii**

Top-Level Field Mission Objectives (Exploration Mission Capabilities):

1. Science/Resource Characterization

A. Perform robotic lunar polar ice/volatile characterization mission (*applicable to Mars and NEOs*)
B. Perform robotic science/resource/site characterization mission with multiple rovers and control centers (*applicable to multiple destinations*)

2. Technology Demonstrations *(NASA Involvement Limited Pending Funding Decisions)*

A. Mobility and human robotic systems
B. ISRU (excavation, landing pads, oxygen/fuel production)
C. Power & Fluid Systems(fuel cells, power management, cryogenic fluid management)

3. Mission Support and Operations

A. Utilize mission representative communications infrastructure and remote operation centers and procedures

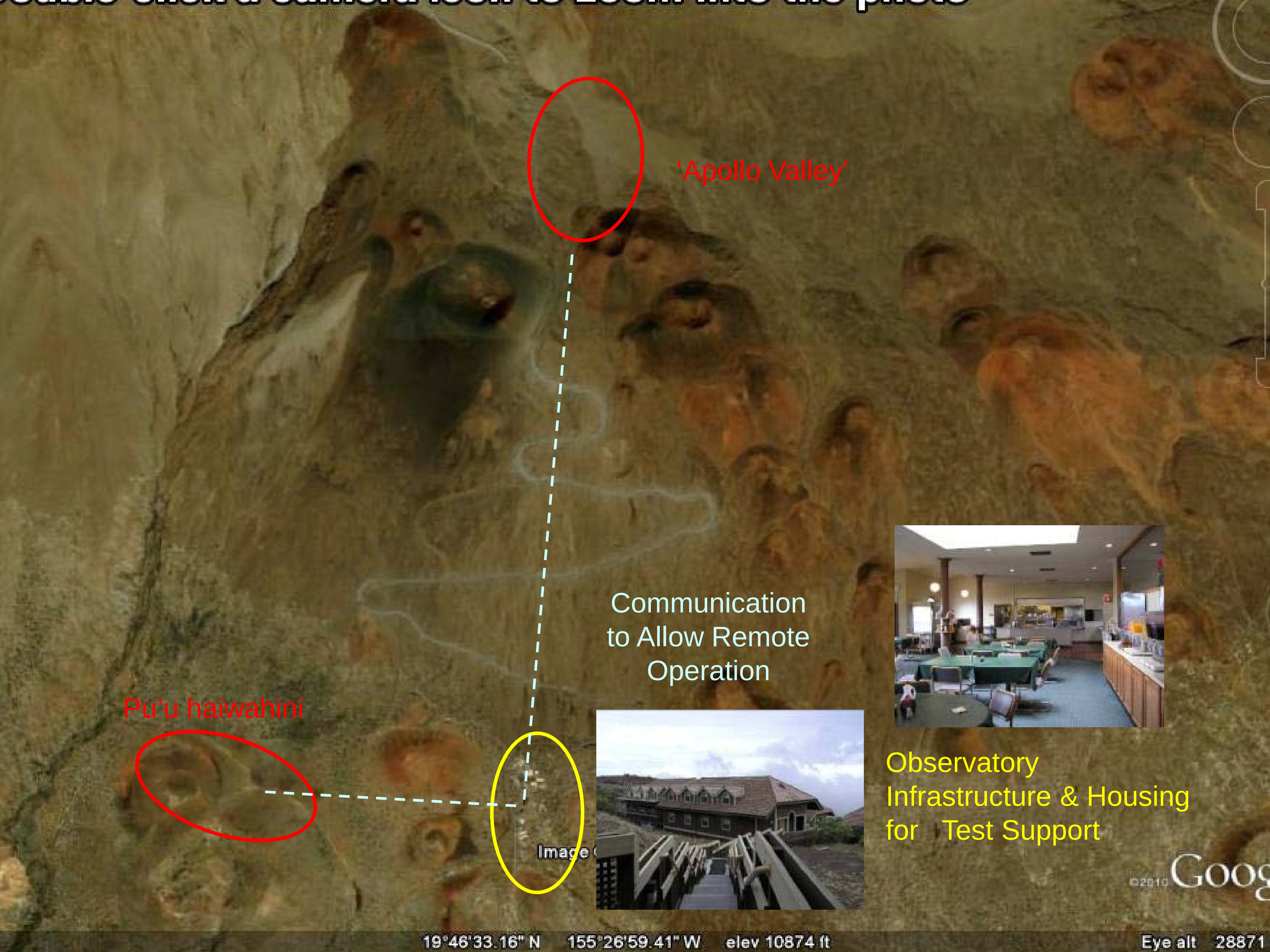
4. Human Medical Tele-Operations

A. Advanced Astronaut Medical Support Concepts & Technologies (patient simulator, ultrasound …)
B. Use combination of representative candidates at the field test with remote specialists

5. Human Exploration Field Test Involvement

A. Human-capable EVA rover mobility testing
B. Field science prospection missions humans, rovers & technologies

Public Outreach, Education, and "Participatory Exploration" is Critical to All Objectives


'Apollo Valley'
Communication
to Allow Remote
Operation
Pu'u haiwahini
Observatory
Infrastructure & Housing
for Test Support
19°46'33.16" N
155°26'59.41" W
elev 10874 ft
Eye alt 28871

Objective 1A: Polar Science – Resource Characterization Mission

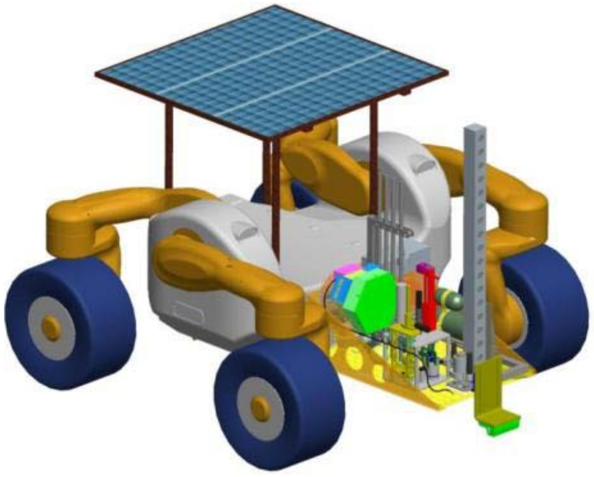
Purpose: Demonstrate Integrated Mobility Platform/Science Payload for Polar Ice/Volatile Mission

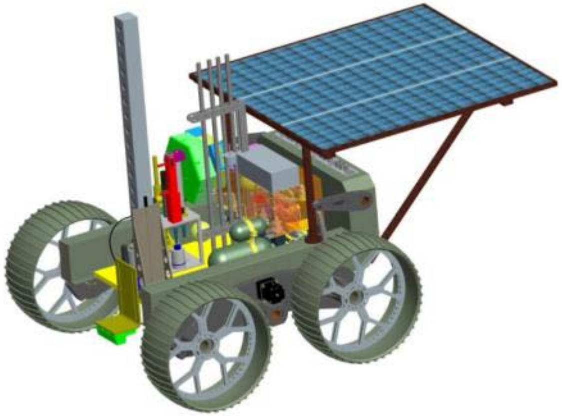
- Perform 1 or more mission scenarios remotely with all hardware/capabilities required

Questions to Be Addressed

- What science & resource characterization instruments should be mounted on a single platform?
- How are operations and data collection effected by control from multiple control centers?
- How does remote scientist involvement (in the loop?) impact productivity?
- How are operations effected by Remote Operations, Power, and level of Autonomy?
- Are navigation capabilities sufficient to for mission scenarios evaluated?

NASA Rover Mounted





CSA Rover Mounted

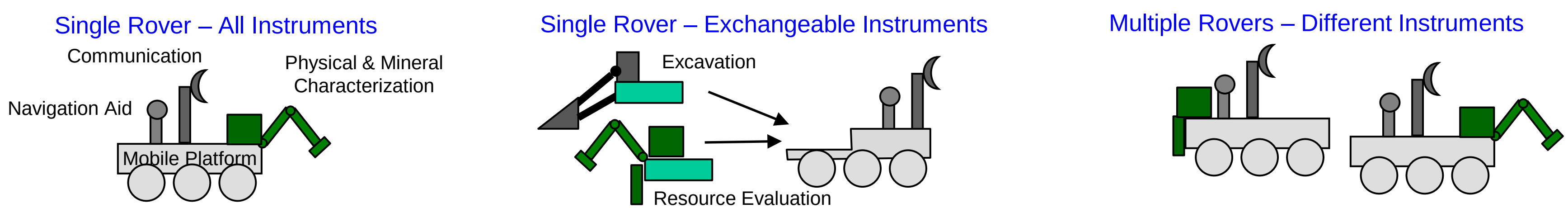
Objective 1B: Perform Robotic Resource and Terrain Site Characterization

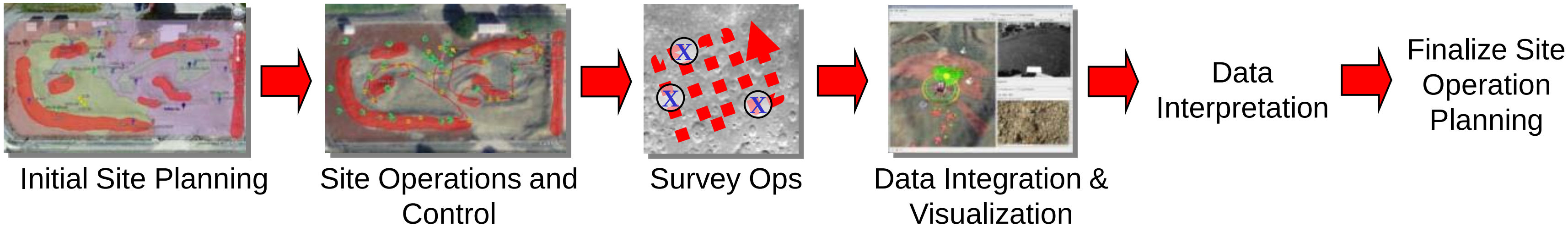
Purpose: Demonstrate instruments and operations associated with performing terrain and resource site characterization before crew arrive

- To evaluate operation concepts and instrument effectiveness with characterizing physical/mineral resources and site terrain; Single vs Multiple Rovers (International)
- Extend Science/Site Characterization operations and instruments from Objective 1A

Questions to Be Addressed

- How do science and resource prospecting site characterization differ? Instruments & Ops
- Can multiple rover/instrument operations be coordinated remotely? By Multiple Ops centers in different time zones
- How does rover size (micros) or number of instruments on each rover impact science performed over specified time?
- How does remote scientist involvement (in the loop?) impact productivity? Multiple Ops centers
- How are operations effected by Communications (time delays) and Level of Autonomy





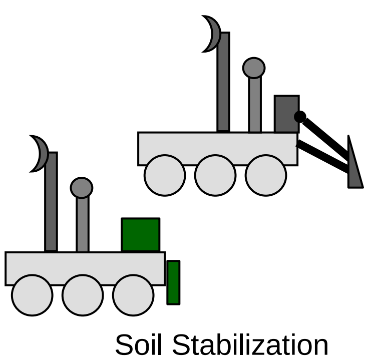
Objective 2: Technology Demonstrations
(NASA Involvement Limited Pending Funding Decisions)

Purpose: Demonstrate all aspects associated with Mars soil and atmospheric processing at relevant scale for demonstration mission

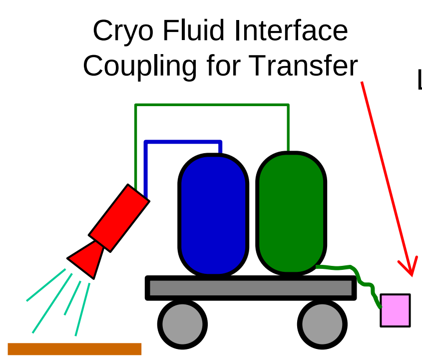
- Build off of and demonstrate commonalities with Lunar ISRU
- Tele-operated/autonomous excavation, regolith delivery/removal, and landing pad construction
- Mars water extraction with reactor, water electrolysis, & regolith transfer
- Mars atmosphere processing with Sabatier for methane (CH_4) production
- Liquid O_2 and Gaseous H_2 storage and regeneration; examine standardized interfaces
- Zero loss O_2 (and CH_4) cryogenic fluid transfer in dusty environment
- Integrate Fuel Cell for nighttime power

Questions to Be Addressed

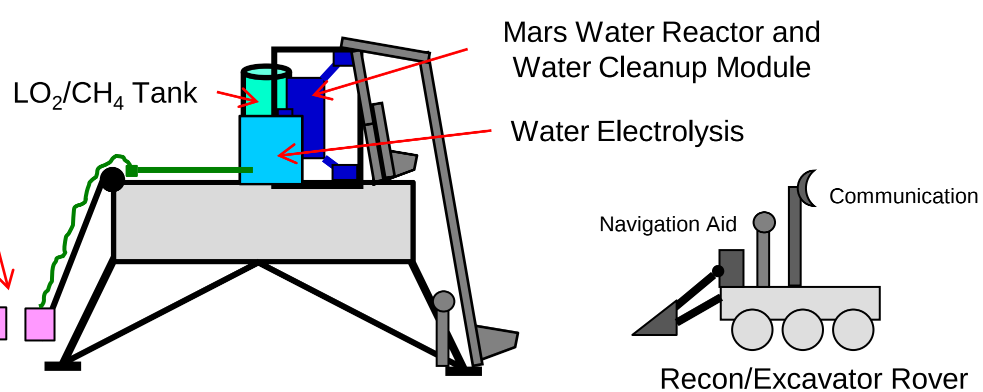
- Can all hardware be mounted and deployed from a lander mockup at relevant mission scales?
- Can end-to-end operations be performed tele-operated from remote sites and what is the impact of time delays? What operations be performed autonomously?
- Can the products generated be utilized to support further analog site test objectives?
- Can fuel cell system provide adequate nighttime power (with variable demand) with minimum/no oversight?



Clear Landing Pad



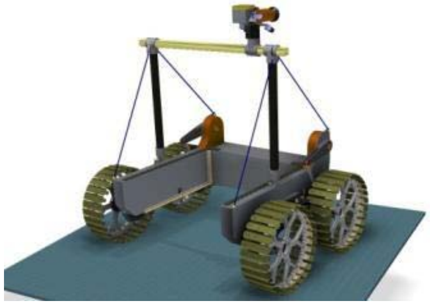
Plume-Soil Interaction Test



Lunar/Mars Propellant Production

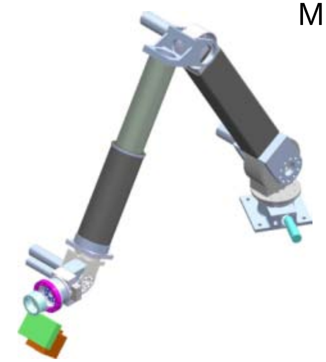
Potential CSA Supplied Hardware

Artemis Jr Rover(<190 kg)



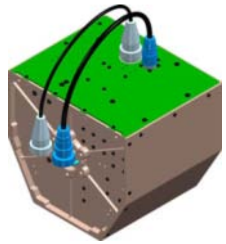
Kapvik Micro-Rover (30 kg)

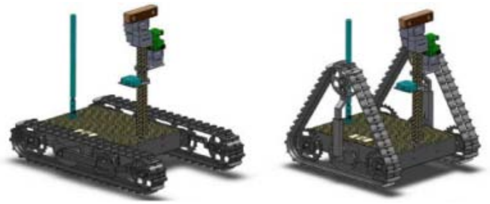
Mini Corer



Small Manipulator Arm (1 m, 6 DoF)

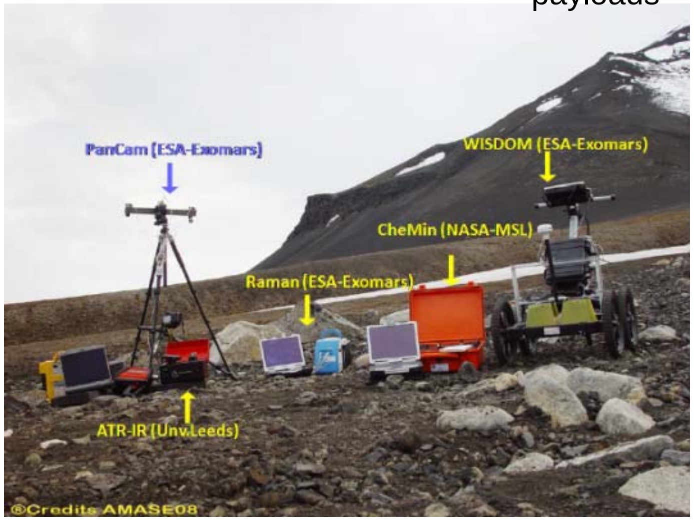
Three-D Exploration Multispectral Microscope Imager (TEMMI)





MRPTA Micro-Rover (30 Kg)

Juno Rover(s) with related ISRU payloads



E-Commander

RESOLVE 1 m Core Drill & Sample Transfer

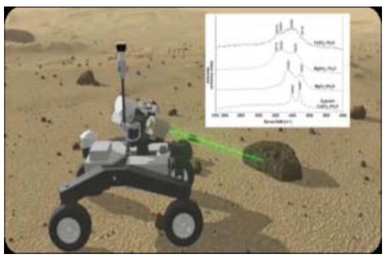
Generic Payload Interface

Tele-medicine patient simulator

Potential NASA Supplied Hardware

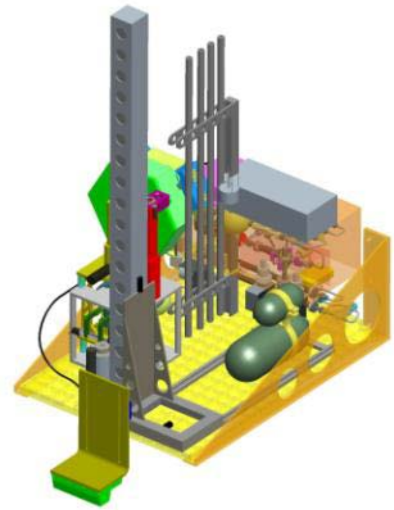
Centaur 2 Rover

K-10 Rover?



LaRC Rover?

RESOLVE



Neutron Spectrometer

Near Infra-Red Spectrometer

Moon-Mars Analog Mission Activity (MMAMA) Instruments

EVA Backpack

In-situ Power and Communications Infrastructure

3rd Analog Field Test Status

- Top-level field test purpose, goals, and objectives approved by NASA and CSA (Dec. 2010)
- A trip to Apollo Valley on Mauna Kea was performed to understand communication impacts and limitations for performing analogue testing for the polar ice/volatile mission scenario near the VLBI antenna. (Mar. 2011)
- NASA and CSA have initiated discussions on communication architecture and roles/responsibilities (Apr. 2011)
- Agreement reached with NASA Science Mission Directorate (SMD) to provide addendum to Moon Mars Analog Mission Activity (MMAMA) ROSES solicitation (May, 2011)
- Grant with University of Hawaii – Hilo awarded to support field test (May, 2011)
- A NASA proposal covering the joint NASA-CSA field test in June 2012, was selected but asked to merge into all NASA analog planning with direction focus on performing a lunar polar ice/volatile characterization and site/resource prospecting mission scenarios with CSA (May, 2011)
- CSA Science provided initial inputs for science objectives and activities to occur at the field test (May, 2011)
- Tentative sites selected for field test activities: Trip for final review planned for Nov. 2011
- NASA Moon Mars Analog Mission Activity (MMAMA) solicitation for science instrument involvement closed (Aug. 26, 2011). Selections this fall.