

Title: **NASA Lunar Mining & Construction Activities and Plans**

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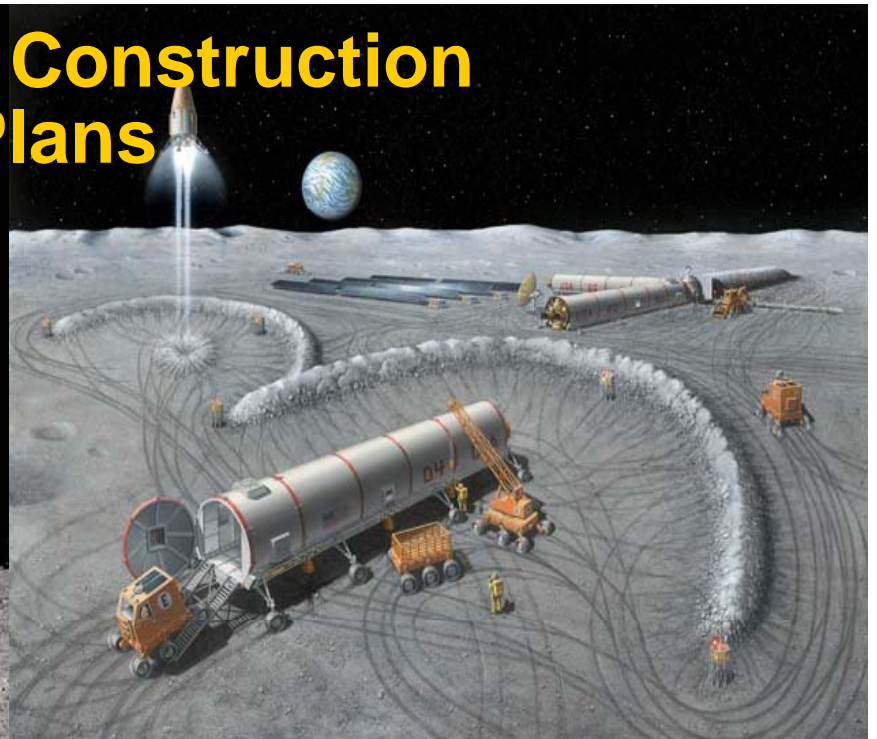
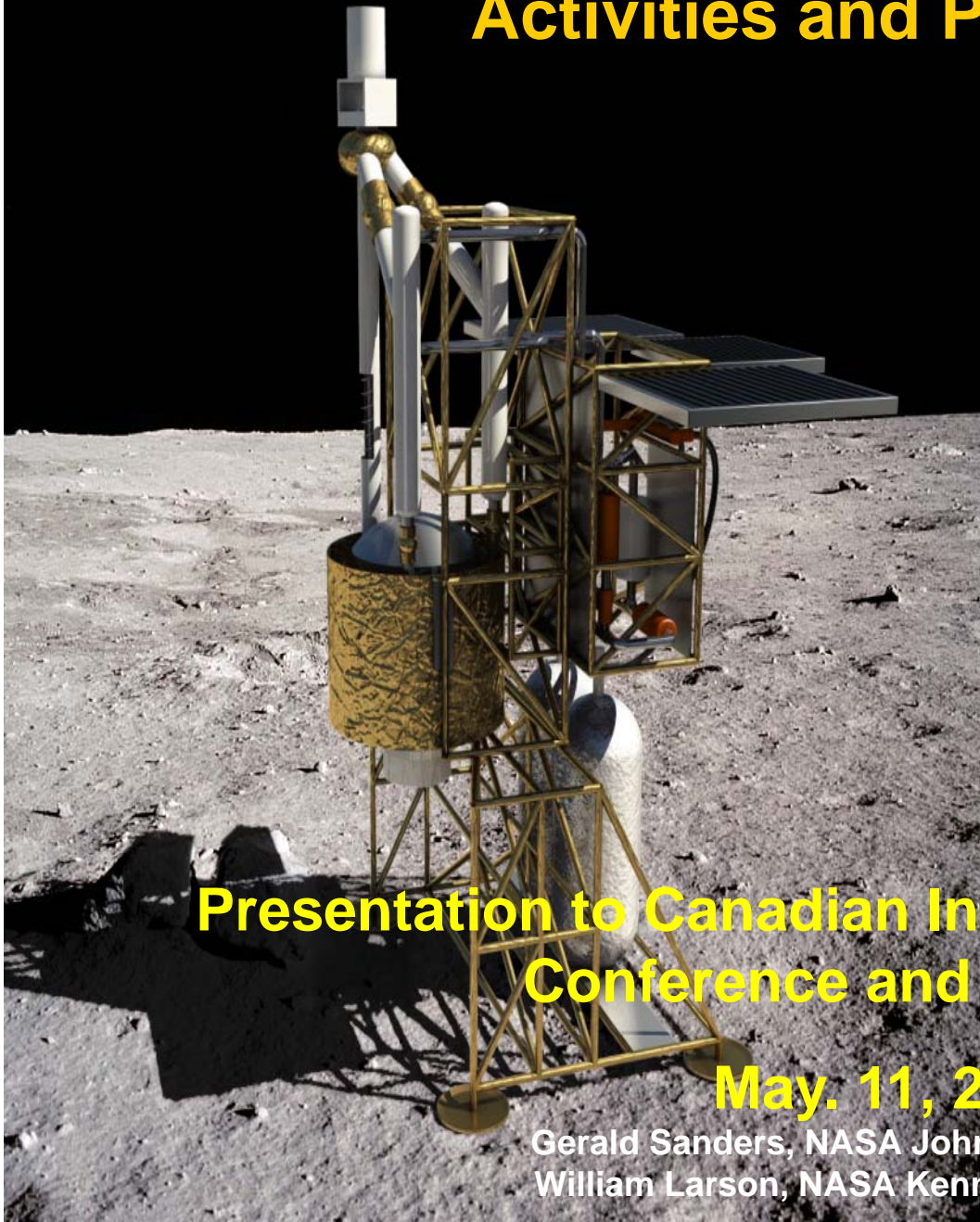
²NASA Kennedy Space Center

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ABSTRACT

The Space Exploration Policy enacted by the US Congress in 2005 calls for the US National Aeronautics and Space Administration (NASA) to 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. In 2006, NASA released the Lunar Architecture Study, which proposed establishing a lunar Outpost on the Moon with international participation to extend human presence beyond Earth's orbit, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth's economic sphere. The establishment of sustained human presence on the Moon for science and exploration combines the design, integration, and operation challenges experienced from both the short Apollo lunar missions and the build-up and sustained crew operations of the International Space Station (ISS). Apollo experience reminds developers and mission planners that hardware must operate under extremely harsh environmental and abrasive conditions and every kilogram of mass and payload must be critical to achieve the mission's objectives due to the difficulty and cost of reaching the lunar surface. Experience from the ISS reminds developers and mission planners that integration of all hardware must be designed and planned from the start of the program, operations and evolution of capabilities on a continuous basis are important, and long-term life-cycle costs and logistical needs are equally or more important than minimizing early development and test costs. Overarching all of this is the need to implement efforts that are sustainable and affordable. One area NASA is developing that can significantly change how systems required for sustained human presence are designed and integrated, as well as potentially break our reliance on Earth supplied logistics, is In-Situ Resource Utilization (ISRU). ISRU, also known "living off the land", involves the extraction and processing of local resources into useful products. In particular, the ability to make propellants, life support consumables, fuel cell reagents, and radiation shielding can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. Also, the ability to modify the lunar landscape for safer landing, transfer of payloads from the lander an outpost, dust generation mitigation, and infrastructure placement and buildup are also extremely important for long-term lunar operations. While extra-terrestrial excavation, material handling and processing, and site preparation and construction may be new to NASA and other space agencies, there is extensive terrestrial hardware and commercial experience that can be leveraged. This paper will provide an overview of current NASA activities in lunar ISRU mining and construction and how terrestrial experience in these areas are important to achieving the goal of affordable and sustainable human exploration.

NASA Lunar Mining and Construction Activities and Plans



**Presentation to Canadian Institute of Mining (CIM)
Conference and Exhibition**

May. 11, 2009

Gerald Sanders, NASA Johnson Space Center
William Larson, NASA Kennedy Space Center



Presentation Topics



- We're Going to the Moon Again?
- What is Lunar Mining – In-Situ Resource Utilization?
- What Are The Challenges to Lunar Mining?
- What is NASA Currently Doing?



NASA Lunar Exploration Overview

A New Vision for NASA

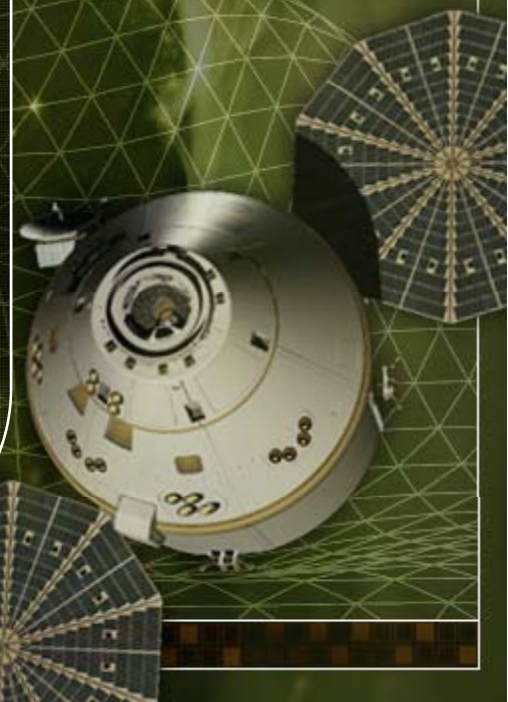
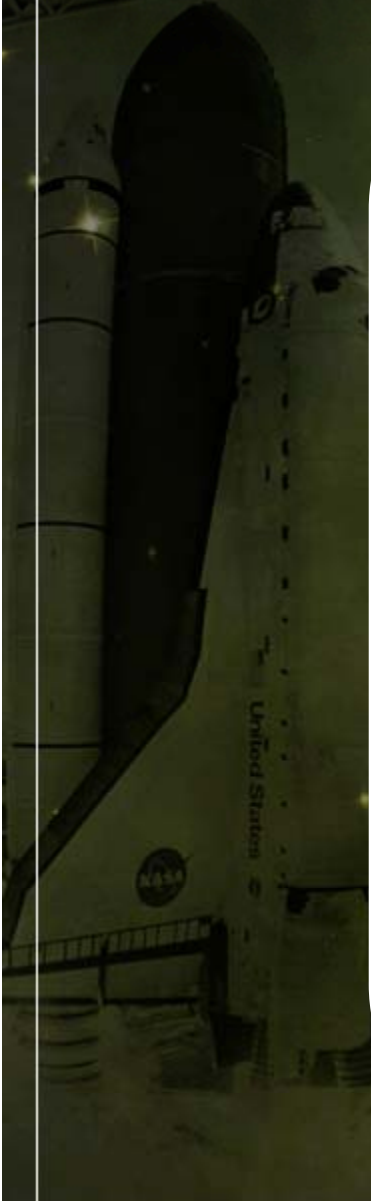
NASA Authorization Act of 2005

The Administrator shall establish a program to develop a sustained human presence on the moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations.

NASA'S PLAN FOR SPACE EXPLORATION



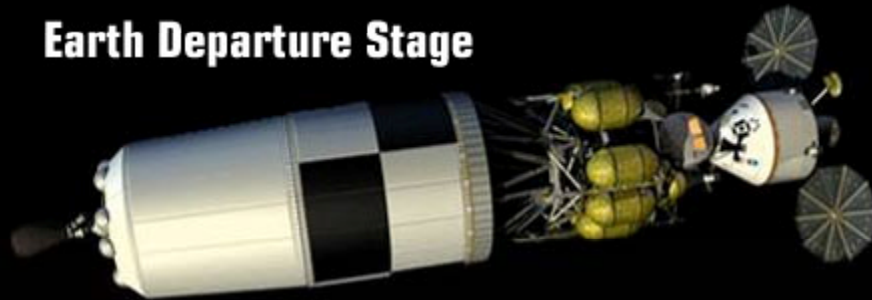
- Complete the International Space Station
- Safely fly the space shuttle until 2010
- Develop and fly the Orion crew exploration vehicle no later than 2015
- Return to the moon no later than 2020 and robotic program
- Implement a sustained and affordable human
- Use the moon to prepare for future human and robotic missions to Mars and other destinations
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration



COMPONENTS OF THE CONSTELLATION PROGRAM



Earth Departure Stage

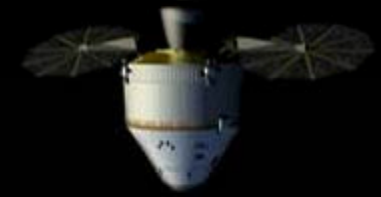


**Orion:
Crew Exploration
Vehicle**

**Ares V:
Heavy Lift
Launch Vehicle**



**Ares I:
Crew Launch Vehicle**



Lunar Lander

BUILDING ON A FOUNDATION OF PROVEN TECHNOLOGIES



Launch Vehicle Comparisons



Space Shuttle

Height: 56m
Gross Liftoff Mass: 2040Mt

25Mt to LEO

Ares I

Height: 98m
Gross Liftoff Mass: 910Mt

22Mt to LEO

Ares V

Height: 109m
Gross Liftoff Mass: 3310Mt

53Mt to TLI
65Mt to TLI in Dual-Launch Mode with Ares I
131Mt to LEO

Saturn V

Height: 111m
Gross Liftoff Mass: 2950Mt

45Mt to TLI
119Mt to LEO

THE LUNAR LANDER

NASA's Goals for Lunar Lander



- Transport 4 crewmembers to and from the surface
 - Visits start with 7 days on surface
 - Length of stays increases step-by-step
 - Builds up to 6 month lunar outpost crew rotations
- Global access capability
- Return to Earth anytime
- Deliver about 16 metric tons of dedicated cargo
- Provide airlock for surface activities
- Descent stage:
 - Liquid oxygen / liquid hydrogen propulsion
- Ascent stage:
 - Storable propellants

CONSTELLATION

ARES I

ARES V

ORION

LUNAR LANDER



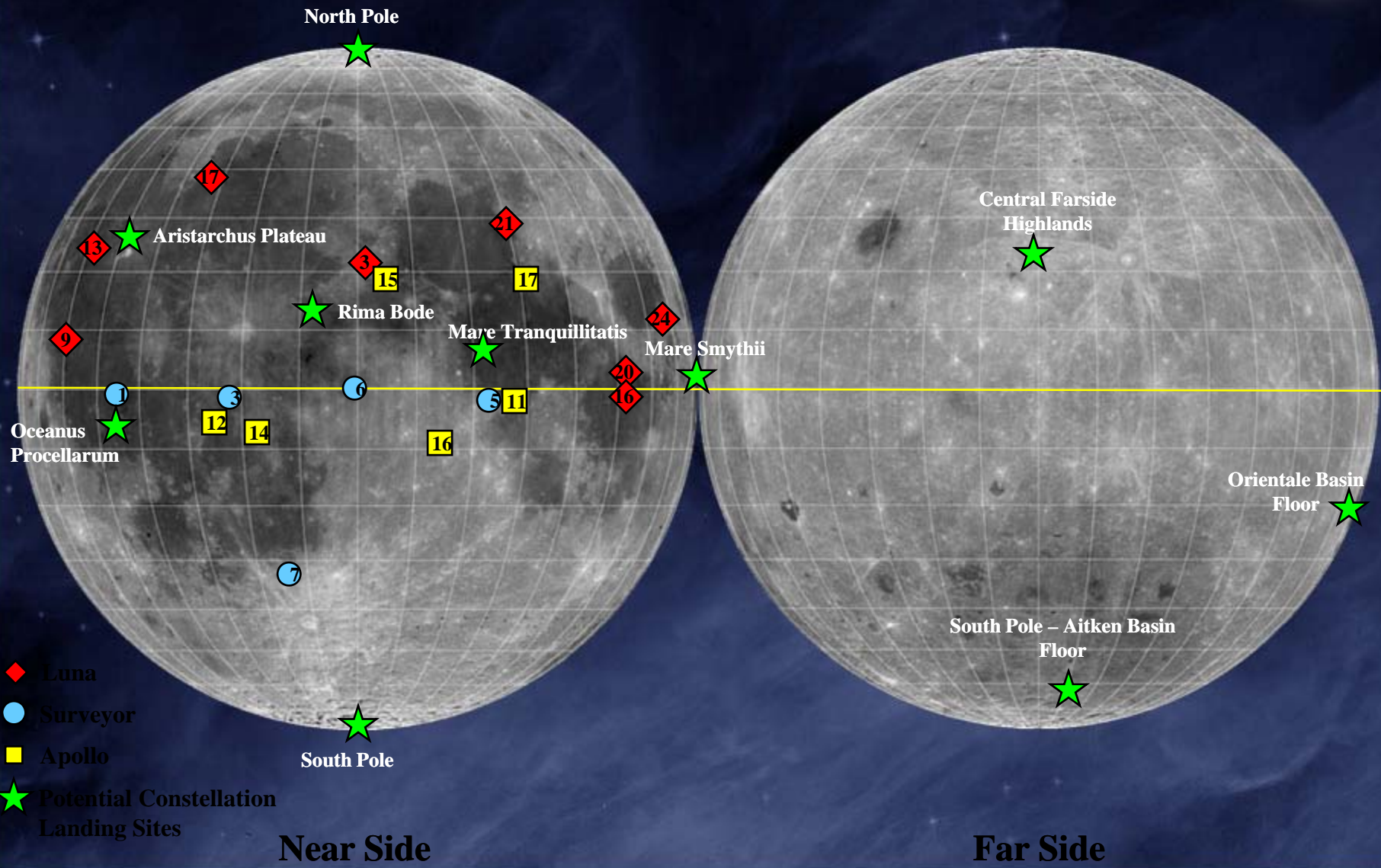
**What Makes Constellation Different
than Apollo?**

We're going there to stay!

CONSTELLATION CAN LAND ANYWHERE ON THE MOON



Previous Missions Landed in Equatorial Band



Conceptual NASA Lunar Surface Architecture

Power & Support Unit (PSU)
(Supports power storage, cargo
offloading & lander)

10 kW Arrays (net)

ISRU
Oxygen
Production
Plant

Logistics
Pantry

Habitation
Element

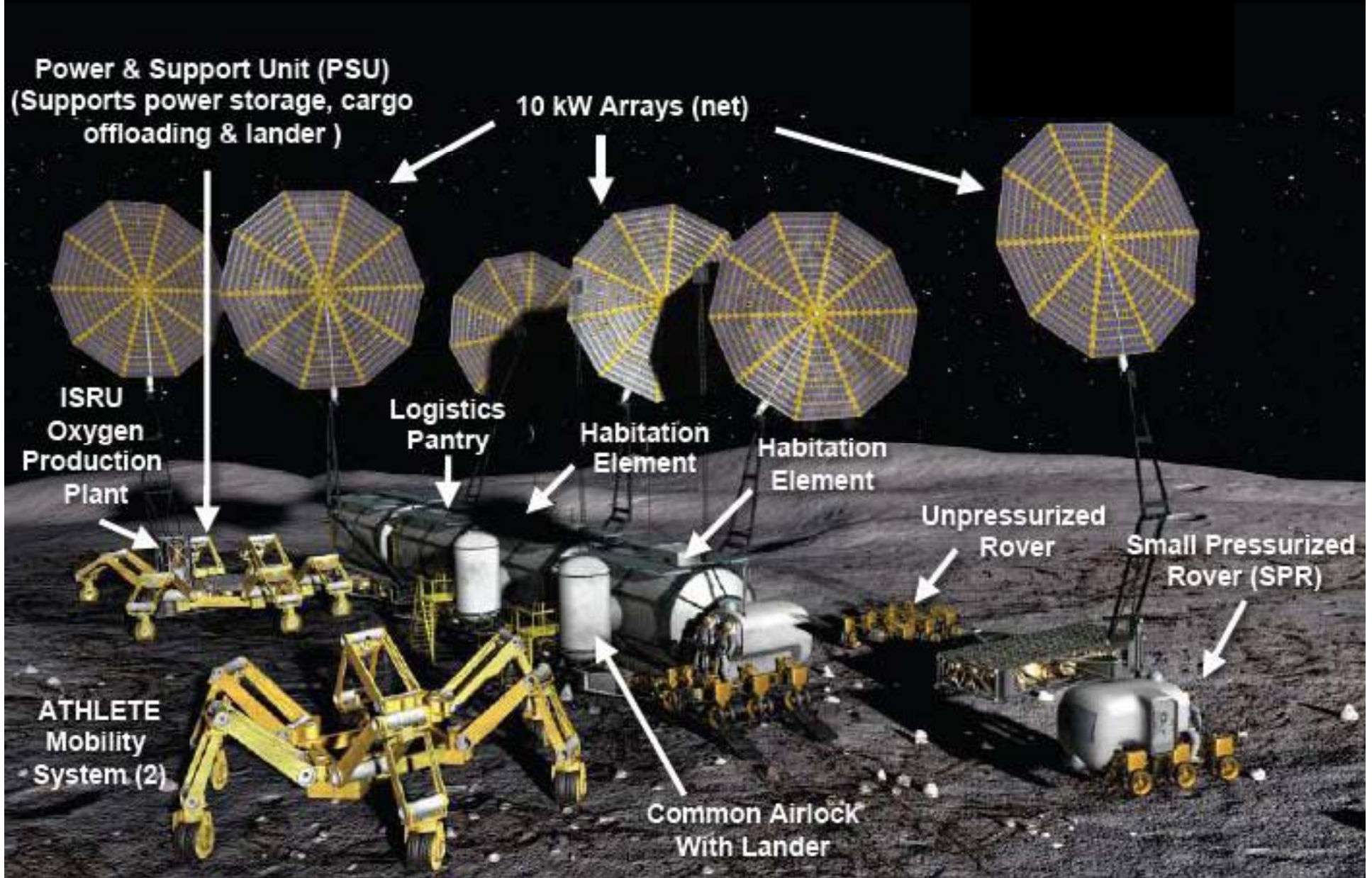
Habitation
Element

Unpressurized
Rover

Small Pressurized
Rover (SPR)

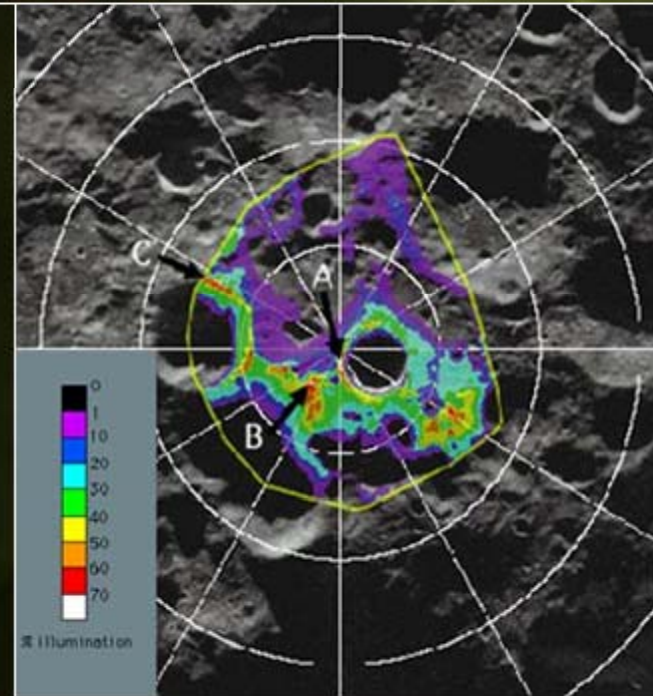
ATHLETE
Mobility
System (2)

Common Airlock
With Lander



POSSIBLE SOUTH POLE OUTPOST

- The lunar South Pole is a likely candidate for an outpost site
- Several areas with greater than 80% sunlight and less extreme temperature swings
- Elevated quantities of hydrogen, possibly water ice in permanently shadowed craters
- Step-by-step outpost construction:
 - Power system
 - Communications/navigation
 - Habitat
 - Rovers



CONSTELLATION

ARES I

ARES V

ORION

LUNAR LANDER



What is Lunar Mining – Space Resource Utilization?

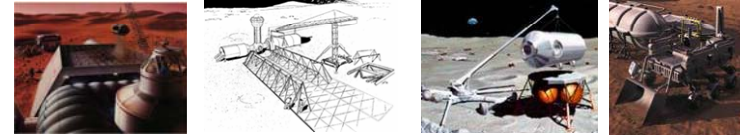


Uses of Space Resources for Robotic & Human Exploration



Mission Consumable Production

- **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- **Life support consumables** (oxygen, water, buffer gases)
 - Gases for science equipment, drilling, and cleaning
 - Bio-support products (soil, fertilizers, etc.)
 - Feedstock for in-situ manufacturing & surface construction



Surface Construction

- **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, plates, water, hydrocarbons, etc.)
- **Landing pad clearance**, site preparation, roads, etc.
 - Shielding from micro-meteoroid and landing/ascent plume debris
 - Habitat and equipment protection



Manufacturing w/ Space Resources

- **Spare parts manufacturing**
 - Locally integrated systems & components (especially for increasing resource processing capabilities)
 - High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)

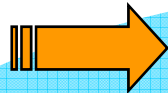


Space Utilities & Power

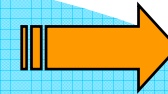
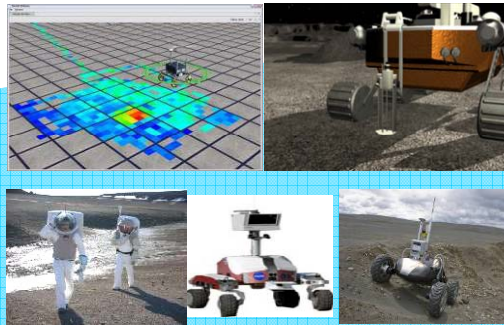
- **Storage & distribution of mission consumables**
 - Thermal energy storage & use
- **Solar energy** (PV, concentrators, rectennas)
- **Chemical energy** (fuel cells, combustion, catalytic reactors, etc.)

Lunar Space Resource Utilization Operation Cycle

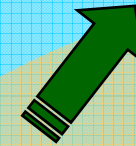
Global Resource Identification



Local Resource Exploration/Planning



Mining



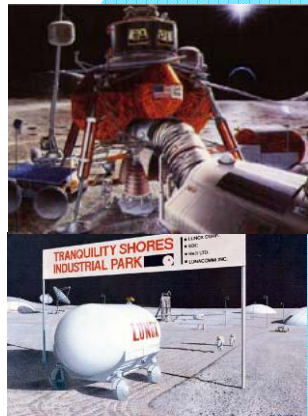
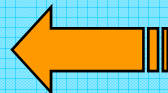
Maintenance & Repair



Site Preparation



Communication & Autonomy

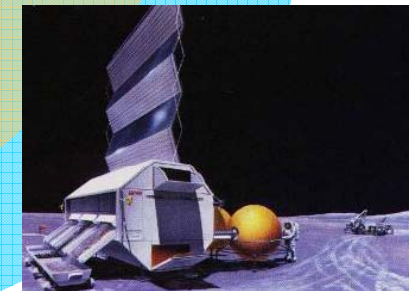
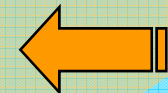


Product & Utilization

Waste



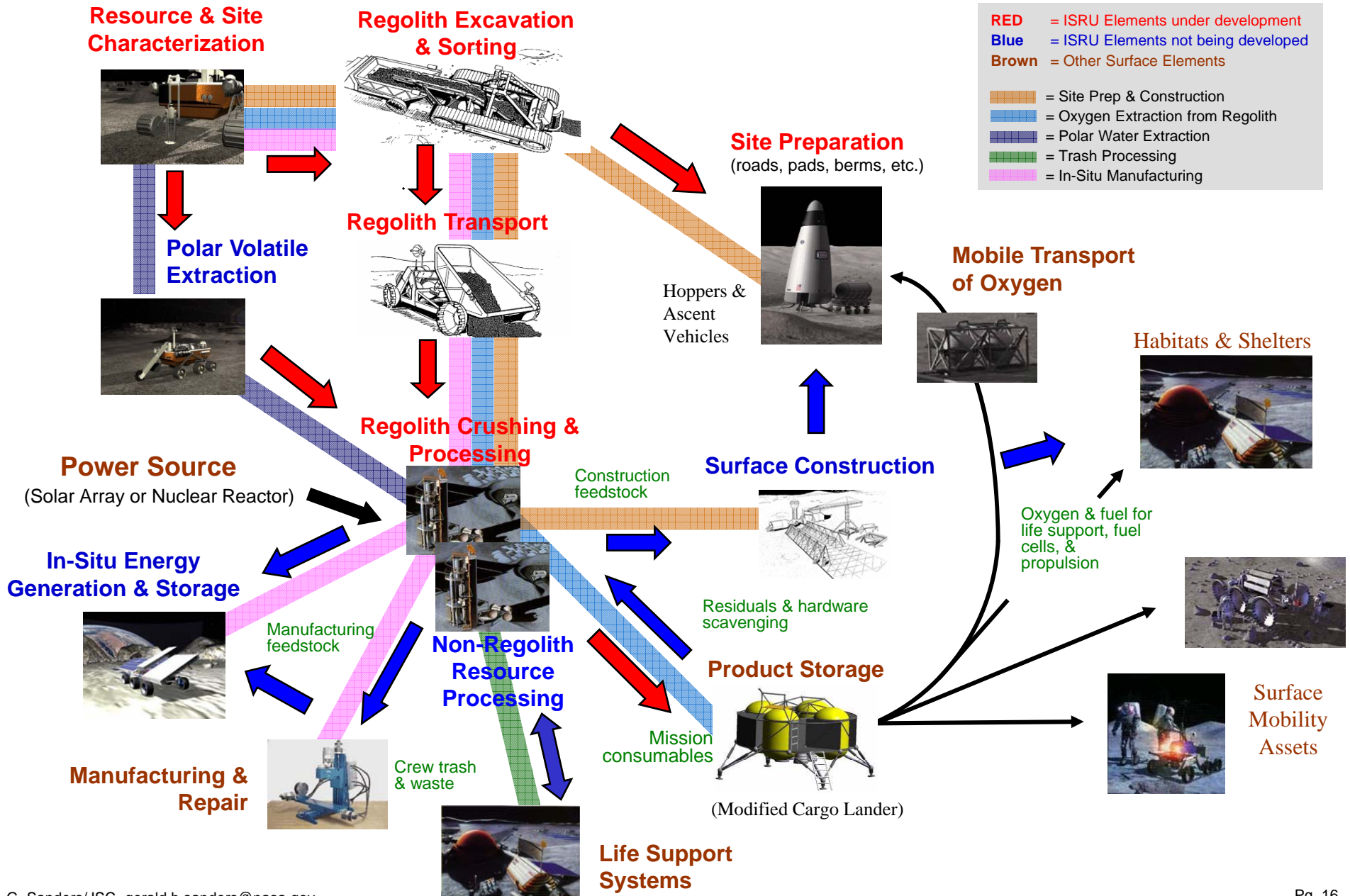
Processing



Crushing/Sizing/
Beneficiation

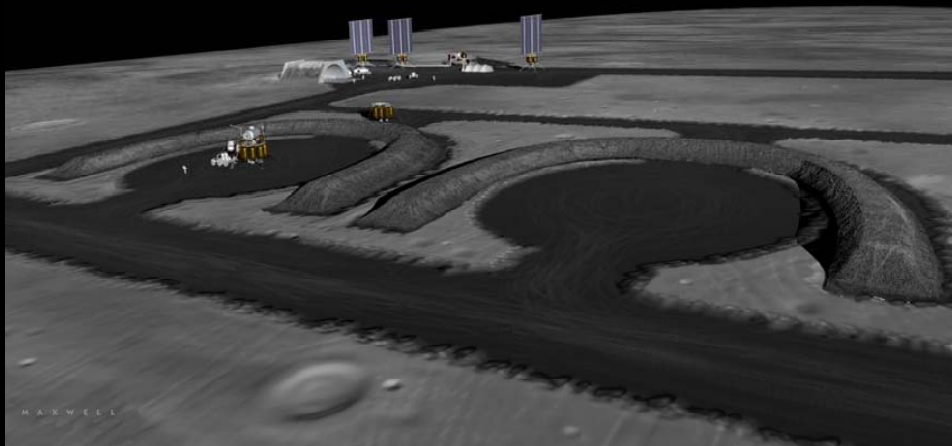


ISRU - Related Surface Elements & Activities



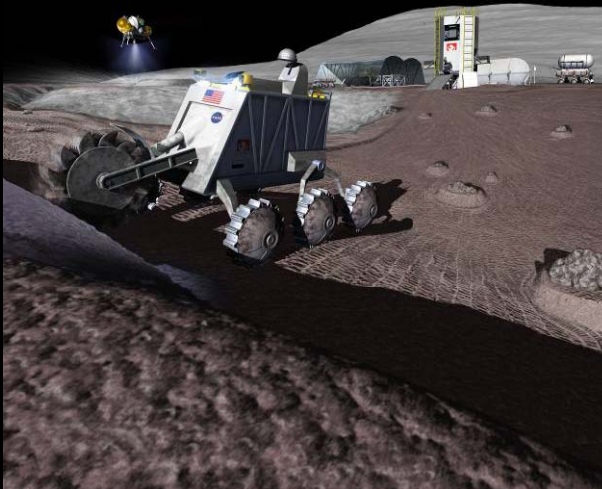
Examples of Lunar Mining & ISRU

Landing Pads, Berm, and Road Construction



Carbothermal Processing with Altair Lander Assets

Excavation & Regolith Processing for O₂ Production



Consumable Depots for Crew & Power



What Are The Challenges?



What Do We Face?



▪ Apollo Heritage

- Design and operation experience and lessons-learned based on up to 3 days of lunar surface operation during lunar 'day' over 35 years ago
- Time needed to prepare hardware for launch did not allow lessons-learned from missions to change subsequent mission hardware
- Lunar simulants used in development were not adequate to prepare for actual operation conditions

▪ ISS Heritage

- Multiple missions required in specific sequence to build up capability
- Highly documented and coordinated interfaces required between participants
- Maintenance, repair, and logistics are critical for long-term operation

▪ Issues Facing all Systems for Robotic & Human Lunar Exploration

- Lunar Sortie & Outpost hardware needs to:
 - Survive months or years with minimum/no maintenance
 - Operate anywhere on the lunar surface and survive/operate during lunar 'night' conditions
 - Operate autonomously/tele-robotically when crew is not present
- Lunar surface elements from different developers will need to be integrated over time
- Science or resource prospecting missions into permanently shadowed craters must operate at <100 K for extended periods of time
- Flight certification testing approach for Shuttle and ISS may not be appropriate
- Limited or no robotic precursor missions available to gain design and operation experience before deployment
- No/Limited lunar environment simulation facilities exist today that can handle lunar simulant and all expected environments



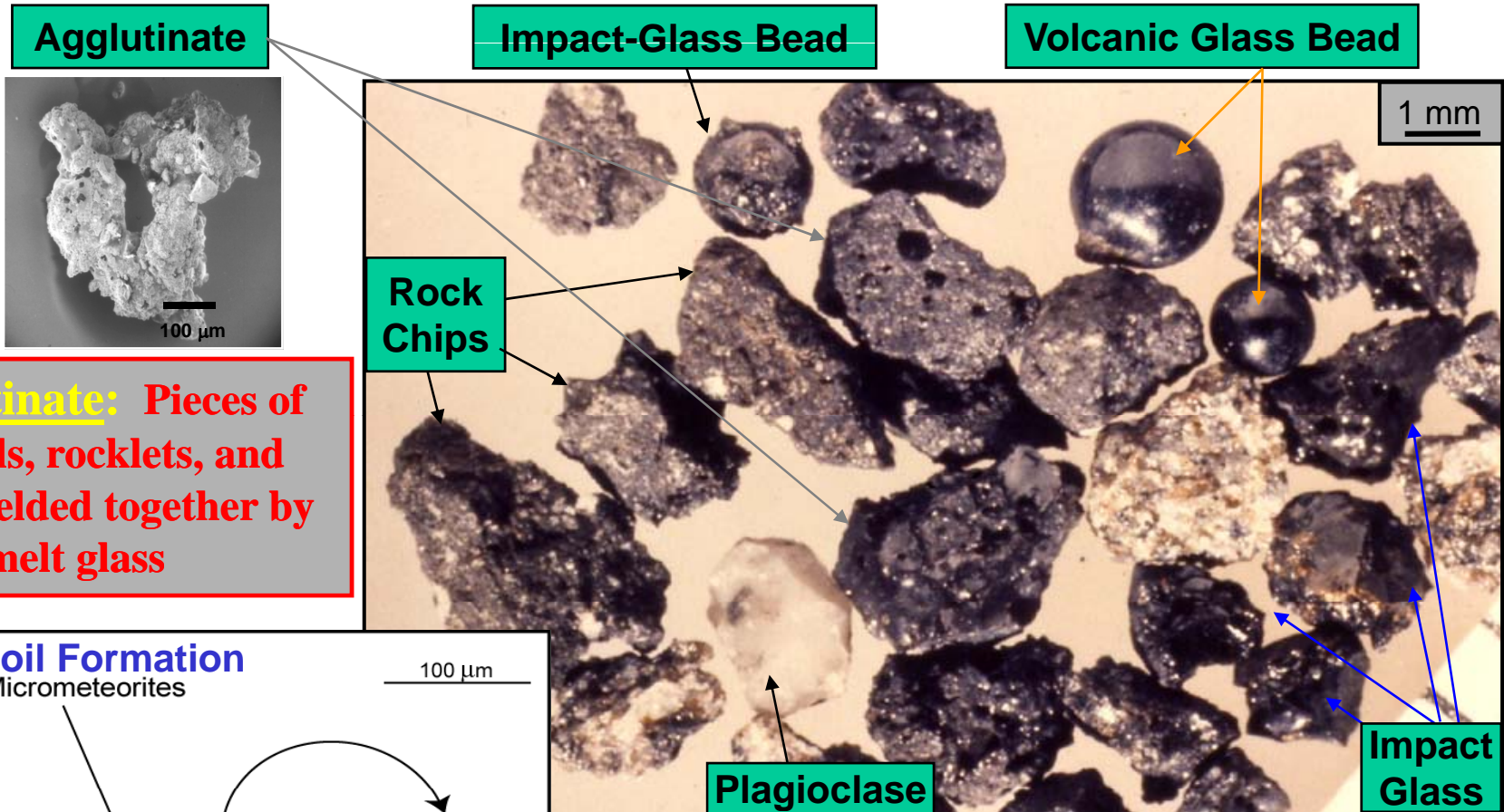
Design & Operation Challenges



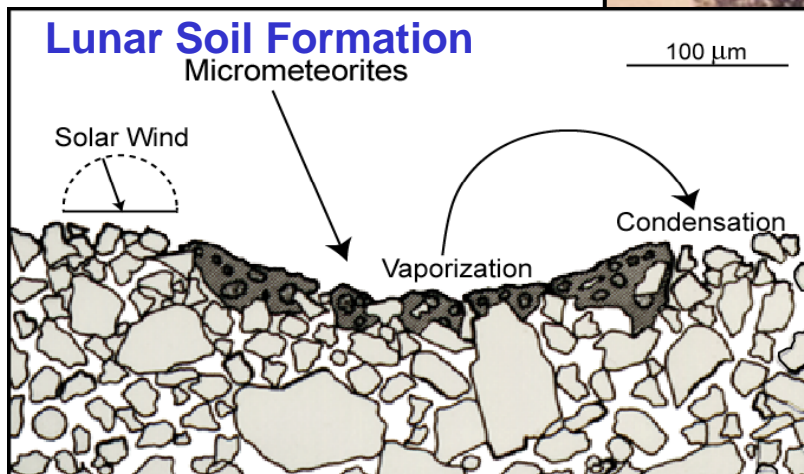
- **Mass & Power:**
 - Cost of transportation to lunar surface means everything needs to be as low of mass and power as possible
- **Environment:**
 - Lunar conditions: vacuum, 1/6 gravity, solar radiation
 - Extreme temperatures (), Permanently shadowed craters down to 40 K
- **Regolith:**
 - Extremely abrasive; Extremely dense/packed;
 - Granular material doesn't flow like on Earth
- **Maintenance:**
 - Must operate for years to be cost effective
 - Astronaut maintenance difficult in vacuum with gloves
 - Minimum spare parts available (logistics)
- **Operation:**
 - Autonomous and tele-operation primarily; 2 second round-trip communication delay with Earth; May not have continuous communication
- **Integration:**
 - Hardware and systems from multiple countries must be compatible with each other to achieve desired capabilities and operations



Lunar Mare Soil



Agglutinate: Pieces of minerals, rocklets, and glass welded together by shock-melt glass



Regolith: broken up rock material
Soil: <1 cm portion of the Regolith
Dust: < 50 μm portion of the Soil

Comminution, Agglutination, & Vapor Deposition

➤ **The bulk of lunar soil is <1 mm in size**

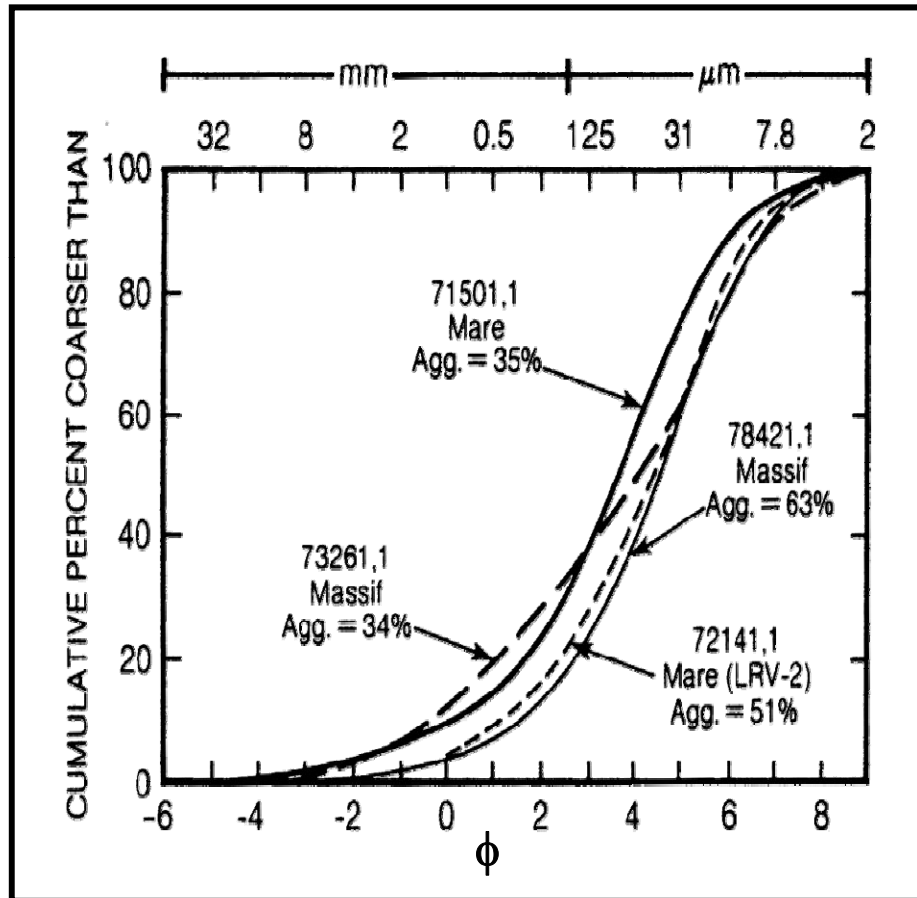


Lunar Soil Characteristics



The bulk of lunar soil is <1 mm in size

Particle Size Distribution



Distribution of particle sizes in separate splits of Apollo 17 soil 78221,8,

Particle Weight Distribution

Soil	Size Fraction					Mean Size, M_z	
	>1 cm	4-10 mm	2-4 mm	1-2 mm	<1 mm	<1cm (mm)	<1mm (mm)
	(weights in grams)						
14163	0.0	196.5	197.1	288.7	4444.0	76	56
15220	0.0	7.0	5.8	2.4	290.0	-	43
68500	1.3	17.3	25.1	37.8	521.1	106	68
72140	1.3	2.7	1.9	5.3	225.9	57	50
72500	3.1	8.0	12.9	24.1	687.2	67	57
73240	1.6	22.3	14.4	14.9	192.7	127	51
74220* *	0.0	0.98	0.17	0.68	7.77	-	41
78220	0.0	1.5	2.7	5.2	227.1	50	45

Weight distribution in size fractions of scooped surface soils.



Lunar Soil Properties



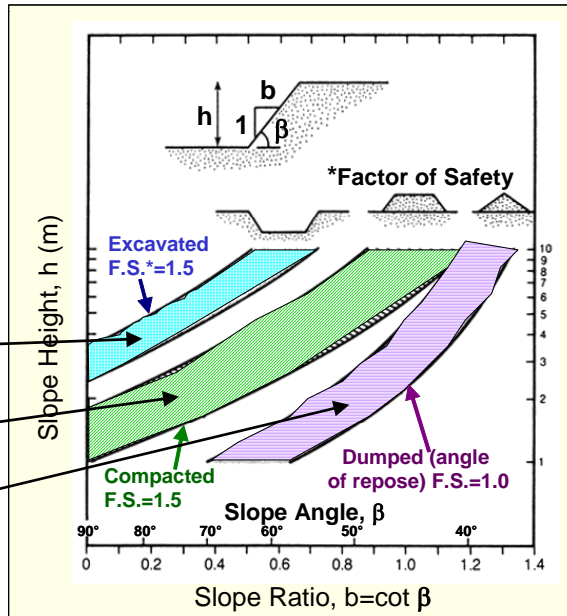
Specific Gravity: Range from 2.3 to >3.2; recommend **3.1** for Engineering use.

Bulk Density: top 15 cm = 1.45-1.55 g/cm³; avg = 1.50 ±0.05 g/cm³
0-30 cm = 1.53-1.63 g/cm³; avg = 1.58 ±0.05 g/cm³
30-60 cm = 1.69-1.79 g/cm³; avg = 1.74 ±0.05 g/cm³
0-60 cm = 1.61-1.71 ±0.05 g/cm³; avg = 1.66 ±0.05 g/cm³
values up to **1.9 g/cm³ estimated at depth of cores to 2.98 m**

Slope Stability

Calculated stability of artificial slopes constructed in lunar surface material. Data are presented for 3 situations:

- (1) an excavation in lunar soil
- (2) a compacted pile of excavated lunar soil
- (3) a dumped pile of lunar soil



A vertical cut can safely be made in lunar soil to a depth of about 3 m; an excavated slope of 60° can be maintained to a depth of about 10 m.

Soil Porosity

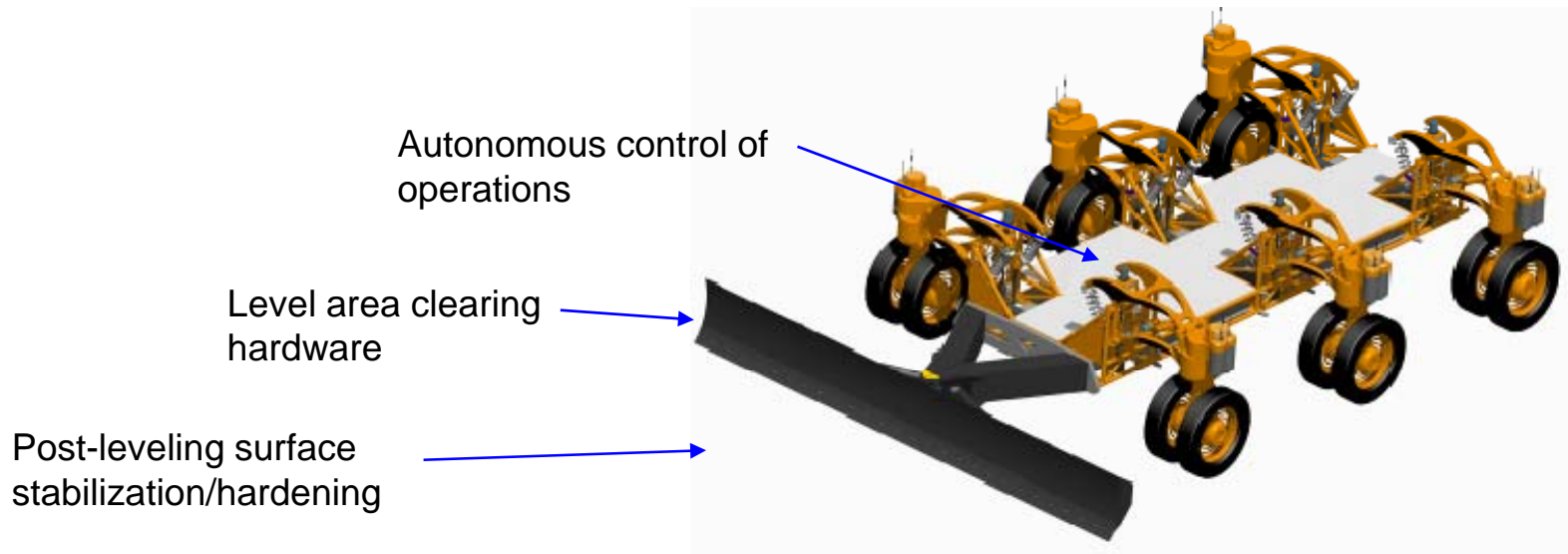
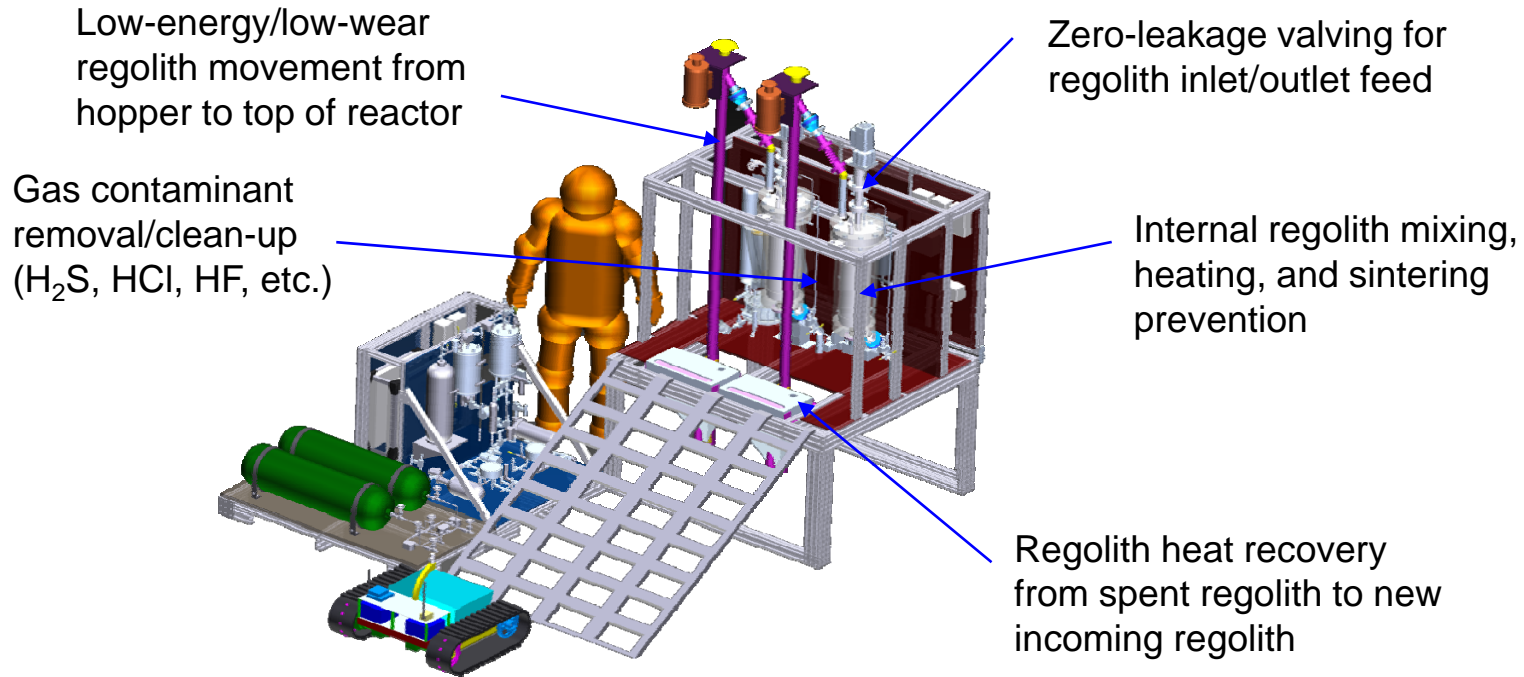
Depth Range (cm)	Average Porosity n , (%)	Average Void Ratio, e
0-15	52 ± 2	1.07 ± 0.07
0-30	49 ± 2	0.96 ± 0.07
30-60	44 ± 2	0.78 ± 0.07
0-60	46 ± 2	0.87 ± 0.07

Lunar soil, in-situ, is very dense, more than that which could be produced with mechanical compaction equipment

– the lunar soil has experienced slow shaking over eons of time.



Examples of Hardware and Operation Challenges

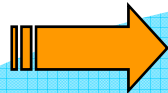




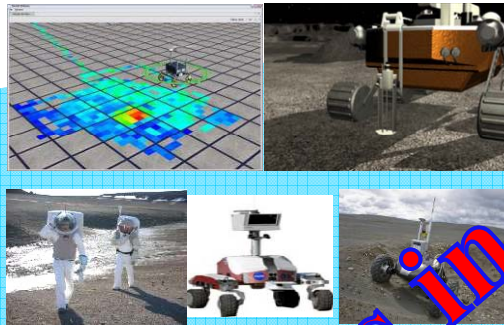
What is NASA Doing?

Lunar Space Resource Utilization Operation Cycle

Global Resource Identification



Local Resource Exploration/Planning



Mining

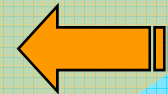
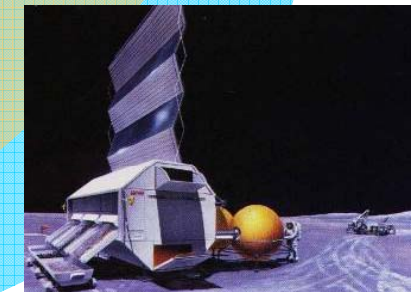


Communication & Autonomy



Site Preparation

Maintenance & Repair



Processing



Waste

Developing all Steps in the Cycle



Product & Utilization



Crushing/Sizing/Beneficiation



Resource Assessment Approach

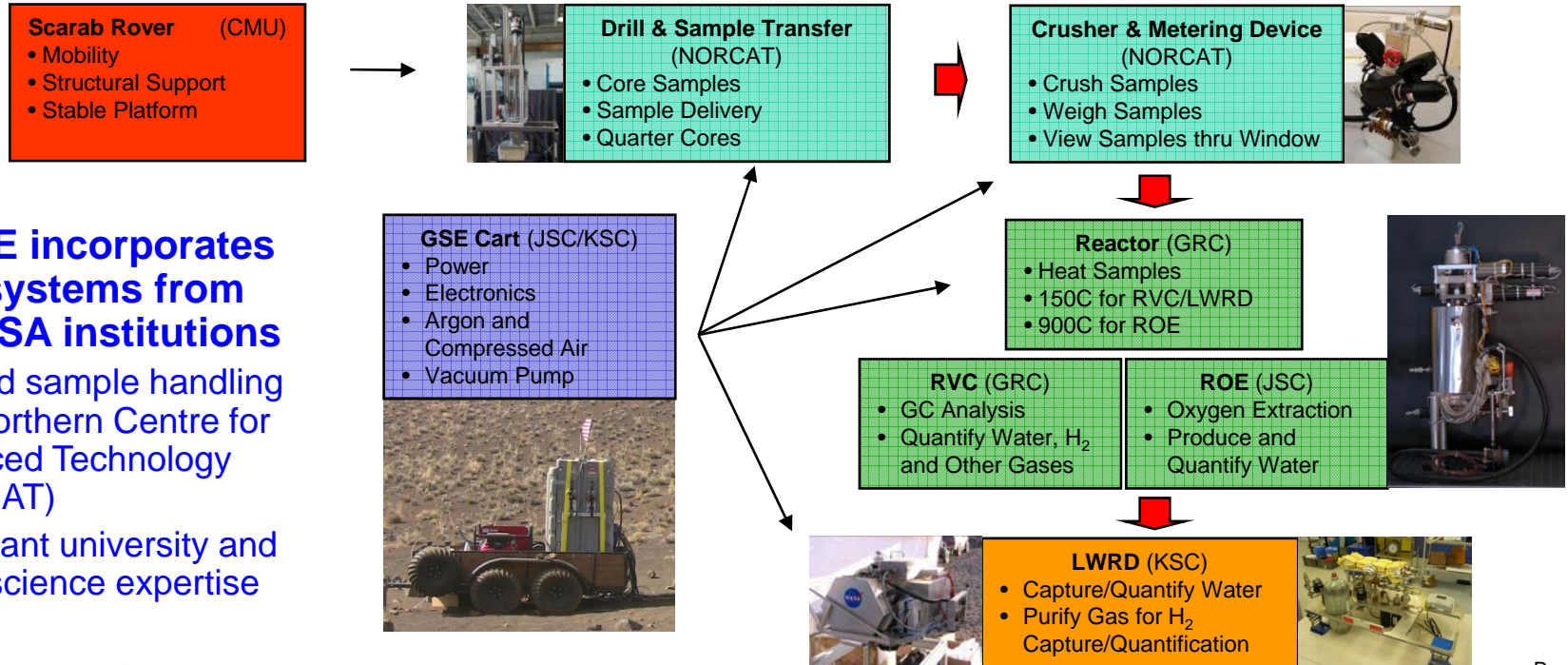


Utilize Orbital Assets to Map Lunar Surface Terrain and Resources

- Lunar Reconnaissance Orbiter & LCROSS

Utilize Instruments on Rovers and Landers - Tie to Science Objectives

- Mineral distribution, especially iron-bearing, within 500 m of Outpost
- Physical characterization; size & shape, rock, glass, and agglutinate content, bulk density, thermal capacity and conductivity, force required to penetrate/dig
- Solar wind volatiles: type, amount, energy required to release
- Permanently shadowed crater resources, esp. hydrogen-bearing, and physical characteristics
- Contaminants released during oxygen extraction processing

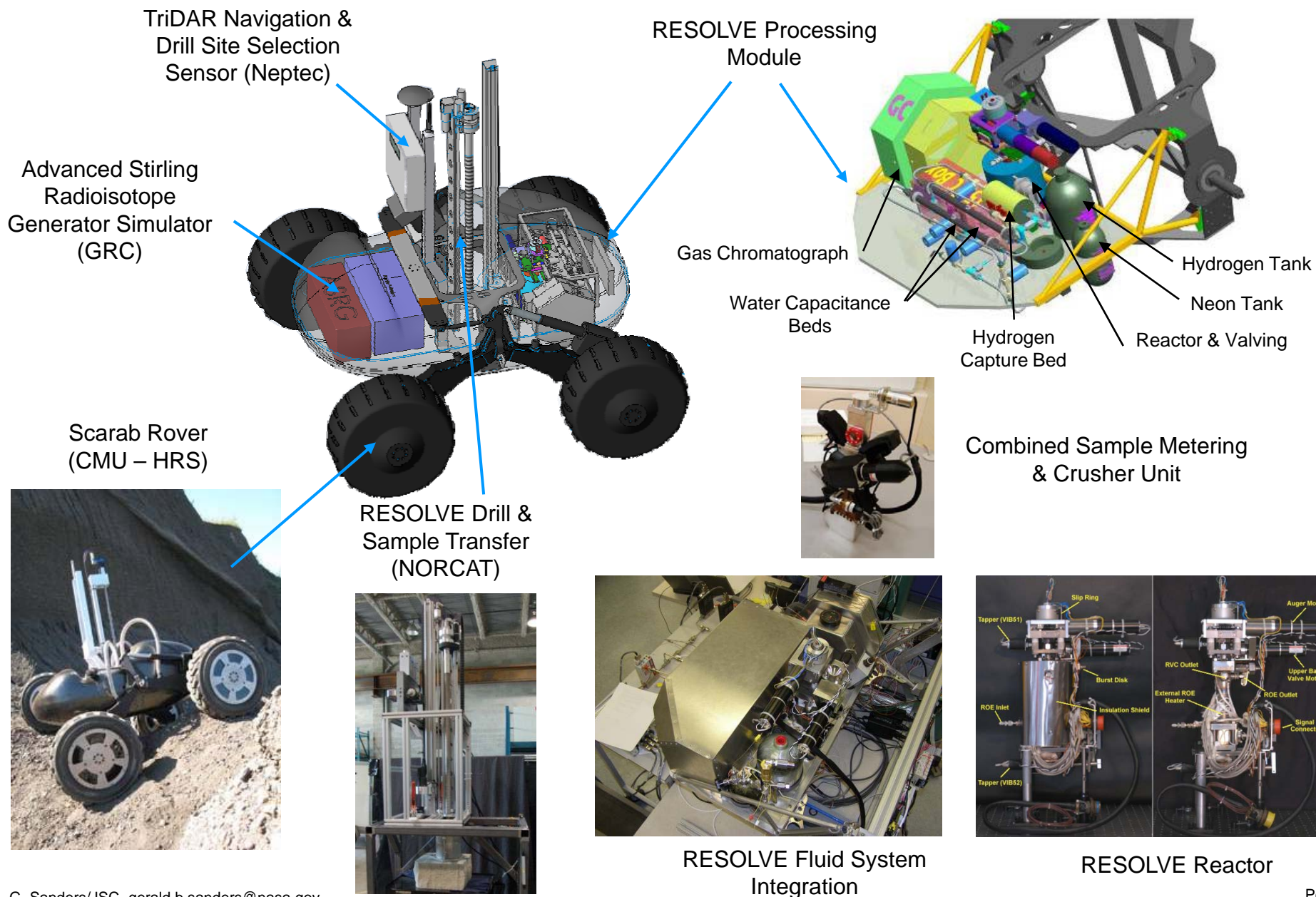


RESOLVE incorporates five subsystems from three NASA institutions

- Drill and sample handling from Northern Centre for Advanced Technology (NORCAT)
- Significant university and Lunar science expertise



Mobile Resource Characterization & Oxygen Production Demonstration Hardware





Lunar Mining & Site Preparation Needs



Excavation for Oxygen Production

- Only need to excavate top loosely consolidated regolith (<8 cm deep)
- For 2 Mt/yr O₂ production with least efficient H₂ Reduction Process
 - > 4% of Chariot time required or
 - > 30% of 2 mini-rovers (250 kg each)
- Options include dedicated vehicle vs part-time usage and integrated excavation-hauler vs separate excavation and hauler vehicles



Site Preparation for Outpost: Landing pads, berms, roads

- Operations can involve area leveling, rock removal, berm building, road/path clearing, and surface hardening (via sintering or binder)
- Largest excavation and regolith movement requirement over life of Outpost
- If landers are not moved, a new pad needs to be prepared *every 6 months*



Operations for Outpost Habitat and Reactor Emplacement

- Multiple options for Habitat protection if regolith shielding for radiation or thermal is desired
 - > Excavate ramp and flat area and drive habitat below surface
 - > Cover inflatable bridge/structure with regolith before inflation
- For nuclear reactor, process depends on excavation vehicle size and method of reactor transport and placement
 - Large vehicle stays outside of hole and uses backhoe
 - Small vehicle excavates ramp/hole and reactor is driven into hole

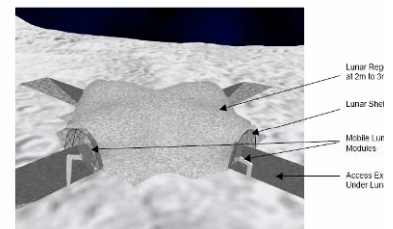
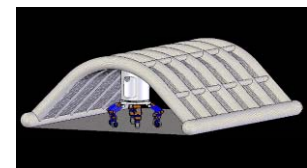


FIGURE 7. Completed Shelter Providing Protection for Mobile Lunar Habitat Modules



Examples of Lunar Mining Activities Underway



Excavation for O₂ Extraction



Site Preparation-Area Clearing



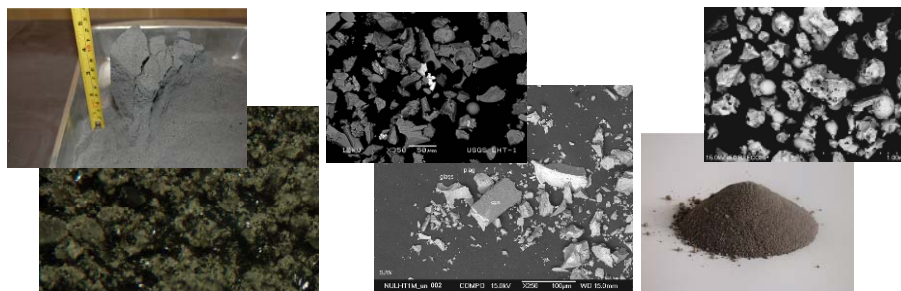
Crushing & Beneficiation



Surface Sintering/Hardening



Lunar Simulant Development



OB1 Highland Simulant (NORCAT/UNB)

Lunar Highland (LHT) Simulant (MSFC-USGS)

JSC1a (ORBITEC)

Credit: Dr. Paul Hintze, KSC





Lunar Processing Consumable Production Needs



■ Oxygen (O₂) Production from Regolith

- 1 mT/yr production rate for ECLSS/EVA closure
- 0.9 mT/yr to make water for ECLSS/EVA closure with lander propellant scavenging
- 9 to 10 mT/yr production rate during Outpost operation would also support refueling 2 ascent vehicles per year to further increase payload delivery capability
- Options include: Hydrogen reduction (1 to 5% kg O₂/kg bulk regolith), Methane Carbothermal reduction (10 to 28%), and Molten electrolysis (up to 40%)

■ In-Situ Water Production

- 0.9 MT/yr water needed for life support/EVA closure
- ~3 MT water needed habitat radiation shielding (3 habitats of 1000 kg each)
- ~225 kg water needed for each Small Pressurized Rover thermal/radiation system (2 minimum)
- Note: Recent architecture evaluations require more water than stated above
- Options include:
 - **Double amount of water produced from propellant scavenging** by adding in-situ oxygen (40 to 60 kg of H₂ remains after all residual O₂ is consumed to make water)
 - Post-ECLSS crew waste/plastic trash processing to complete extraction of water
 - Polar water/ice extraction and processing only needed if large scale in-situ propellant production is used incorporated into the architecture

■ In-Situ Methane Production

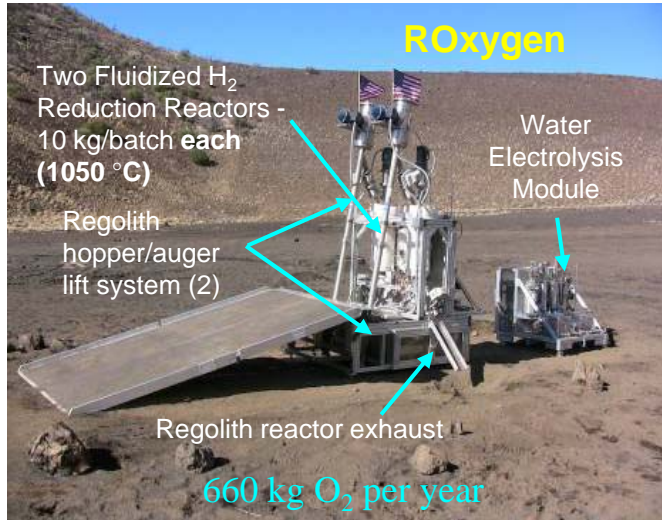
- ~2100 kg/yr supports refueling 2 ascent vehicles per year.
- Capability can be used to initially supports LSAM Ascent 'top-off' in case of leakage, power loss, or increased payload to orbit before completely refueling ascent vehicle
- Options include:
 - Utilize methane produced by habitat life support system (400-500 kg/yr for crew of 4)
 - Process plastic trash and crew waste with in-situ oxygen to make methane



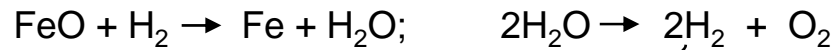
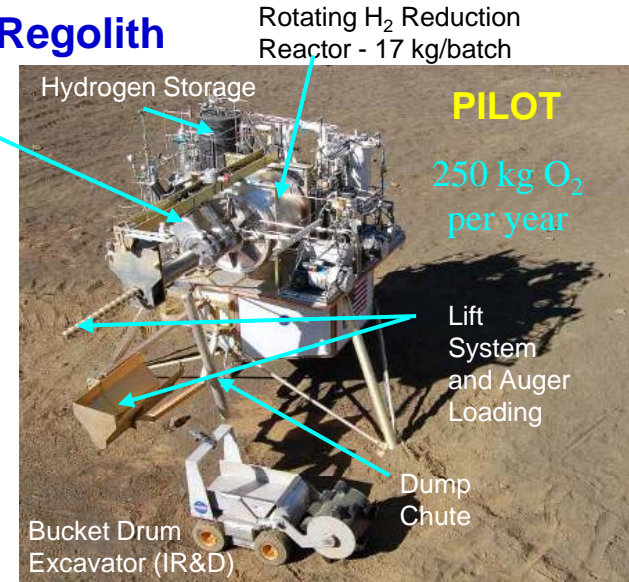
Lunar Processing – Oxygen & Metal Extraction



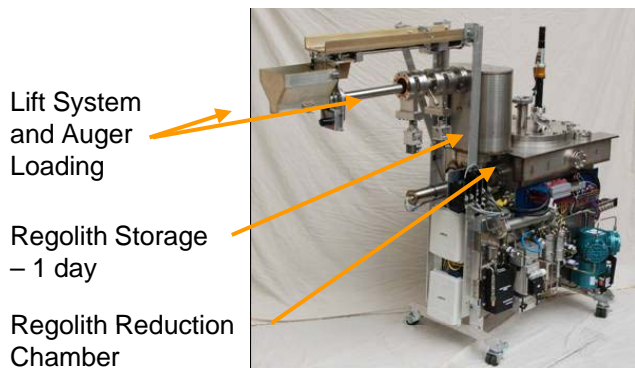
Hydrogen Reduction of Regolith



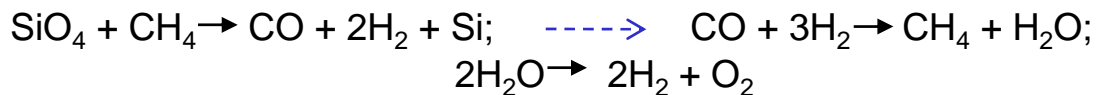
1. Heat Regolith to >900 C
2. React with Hydrogen to Make Water
3. Crack Water to Make O₂



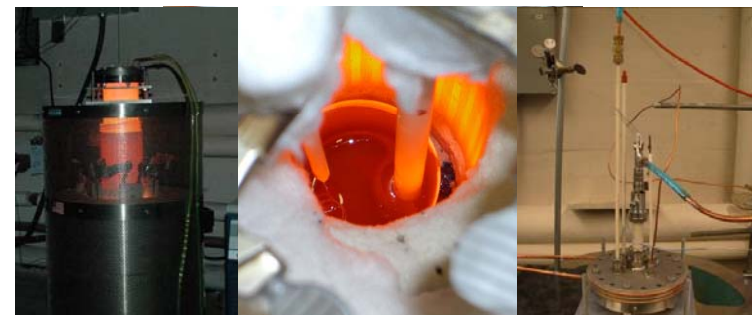
Carbothermal Reduction of Regolith



1. Melt Regolith to >1600 C
2. React with Methane to CO
3. Convert CO to Methane & Water
4. Crack Water to Make O₂



Molten Electrolysis of Regolith



1st Generation of Lunar Mining & Processing Equipment Built and Tested

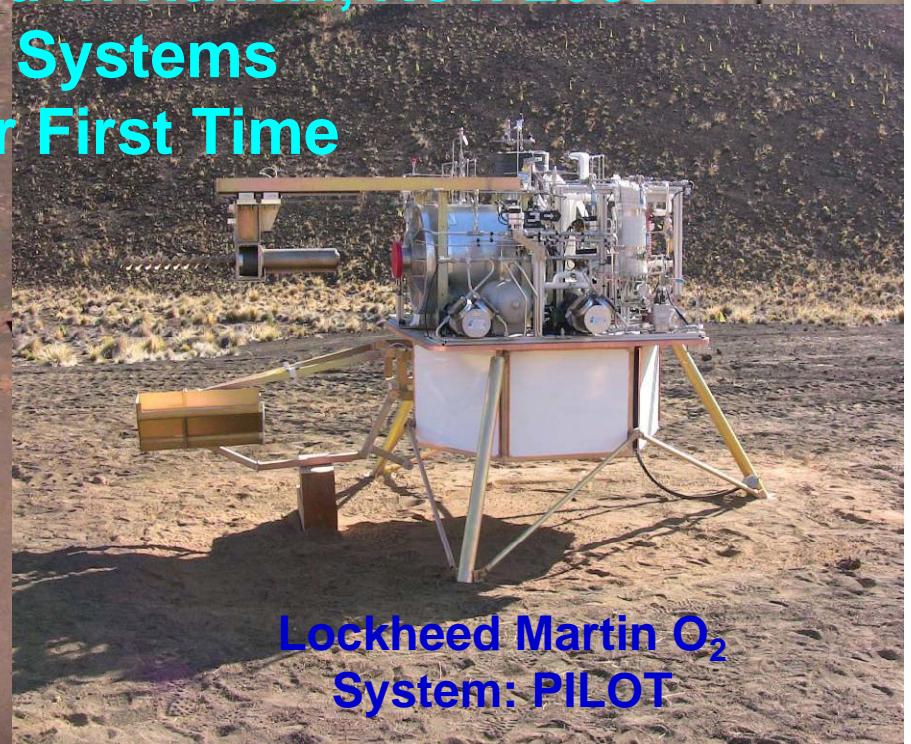
ISRU Systems Field Tested in Hawaii, Nov. 2008
3 Major Systems
Tested for First Time



RESOLVE: Resource Prospector and O₂ Demonstration System



JSC "ROxygen" System



Lockheed Martin O₂ System: PILOT



Next System Field Test in Planning



Advanced Lunar ISRU Cycle Hardware & Operations

Site & Resource Exploration

NORCAT/CSA Platform

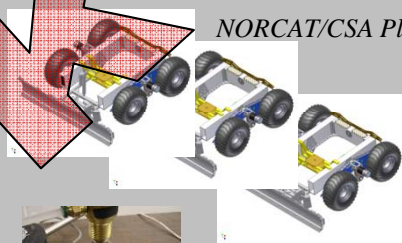


GPR & RESOLVE Drill for subsurface validation

Hand-held and rover mounted CSA & NASA MMAMA Instruments

Site Preparation & Excavation

Autonomous and Tele-operation Area Clearing/Excavation Implement Testing



NORCAT/CSA Platforms



Surface Sintering

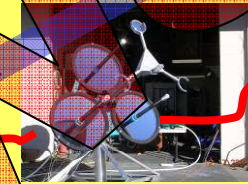
Solar Energy

Upgraded GRC Solar Array Cart

(Power Project Involvement)

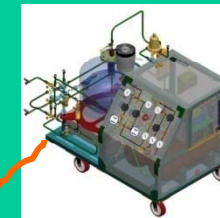


Solar Concentrator



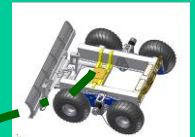
Solar Energy

Product & Utilization



O₂ Liquefaction and Storage (CFM Project Involvement)

CSA Fuel Cell – Hydride Tank Resupply



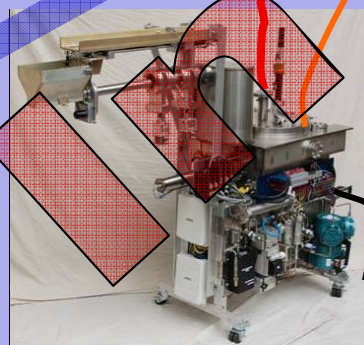
H₂ Storage & Transfer

Mining & Processing

NORCAT/CSA Platform



Tele-operated & Autonomous Excavation and Delivery



Carbothermal Reduction Reactor



Upgraded JSC ROxygen Water Electrolysis

Electricity

H₂O

O₂

H₂



Long-Term Plans to Link Lunar Surface Elements Together



Moses Lake, WA – 6/08



Crew & Tele-operation Non-articulating Area Clearing/Berm Building

Blackpoint Lava, AZ – 9/09



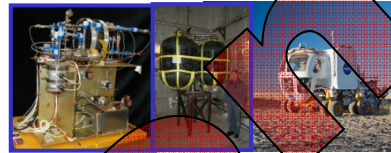
Crew & Tele-operation Articulating Area Clearing/Berm Building on SPR

Desert RATS – 9/10

Fuel Cell w LO_2/GH_2 Storage, Transfer, & Resupply

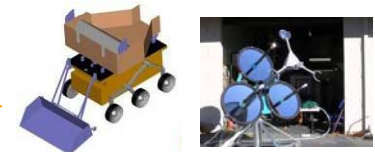


Fuel Cell w GO_2/GH_2 Storage, Transfer, & Resupply



Mauna Kea, HI – 1/11?

Remote Tele-operation and Autonomous Site Excavation for O_2 Production – Surface Stabilization for Rocket Engine Firing



Mauna Kea, HI – 11/08

Local Tele-operation Excavation for O_2 Production



Mauna Kea, HI – 1/10

CSA-NASA Local and Remote Tele-operation and Autonomous Site Preparation & Excavation



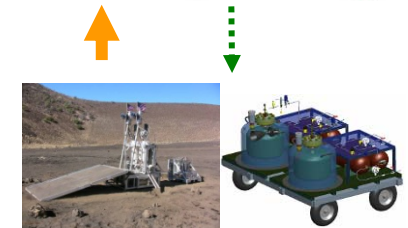
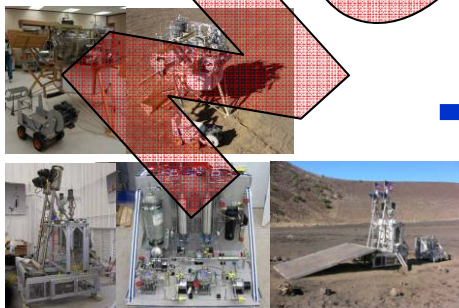
H_2 Transfer and Resupply of CSA Fuel Cell

Solar Surface Sintering



CH_4 Reduction – Solar Energy - Integrated Water Electrolysis – Liquid O_2 Storage. H_2 Transfer

1st Gen H_2 Reduction – Separate Water Electrolysis – Gaseous O_2 Storage – Gas Generator Power



2nd Gen H_2 Reduction – Integrated Water Electrolysis – Liquid O_2 Storage, Transfer, and Propulsion