Space Resource Utilization and Human Exploration of Space

Presentation for the Planetary & Terrestrial Mining Sciences Symposium (PTMSS)

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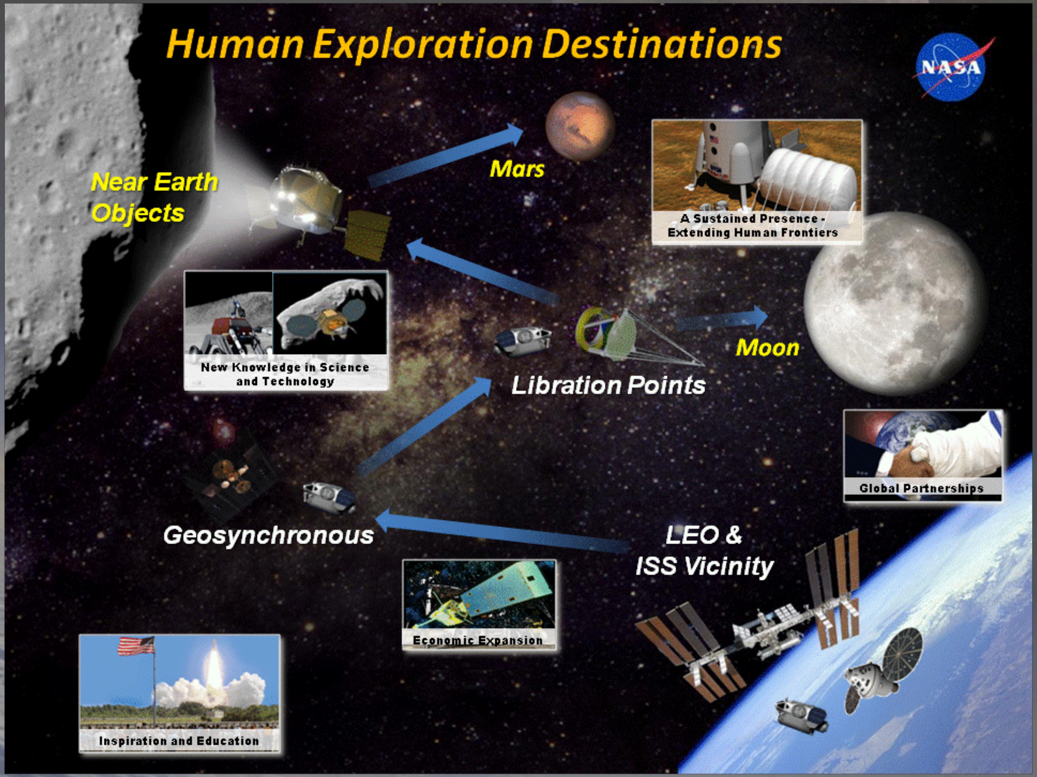
NASA Strategic Goals:

- Extend and sustain human activities across the solar system
- Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.
- Create the innovative new space technologies for our exploration, science, and economic future

Affordable and Sustainable

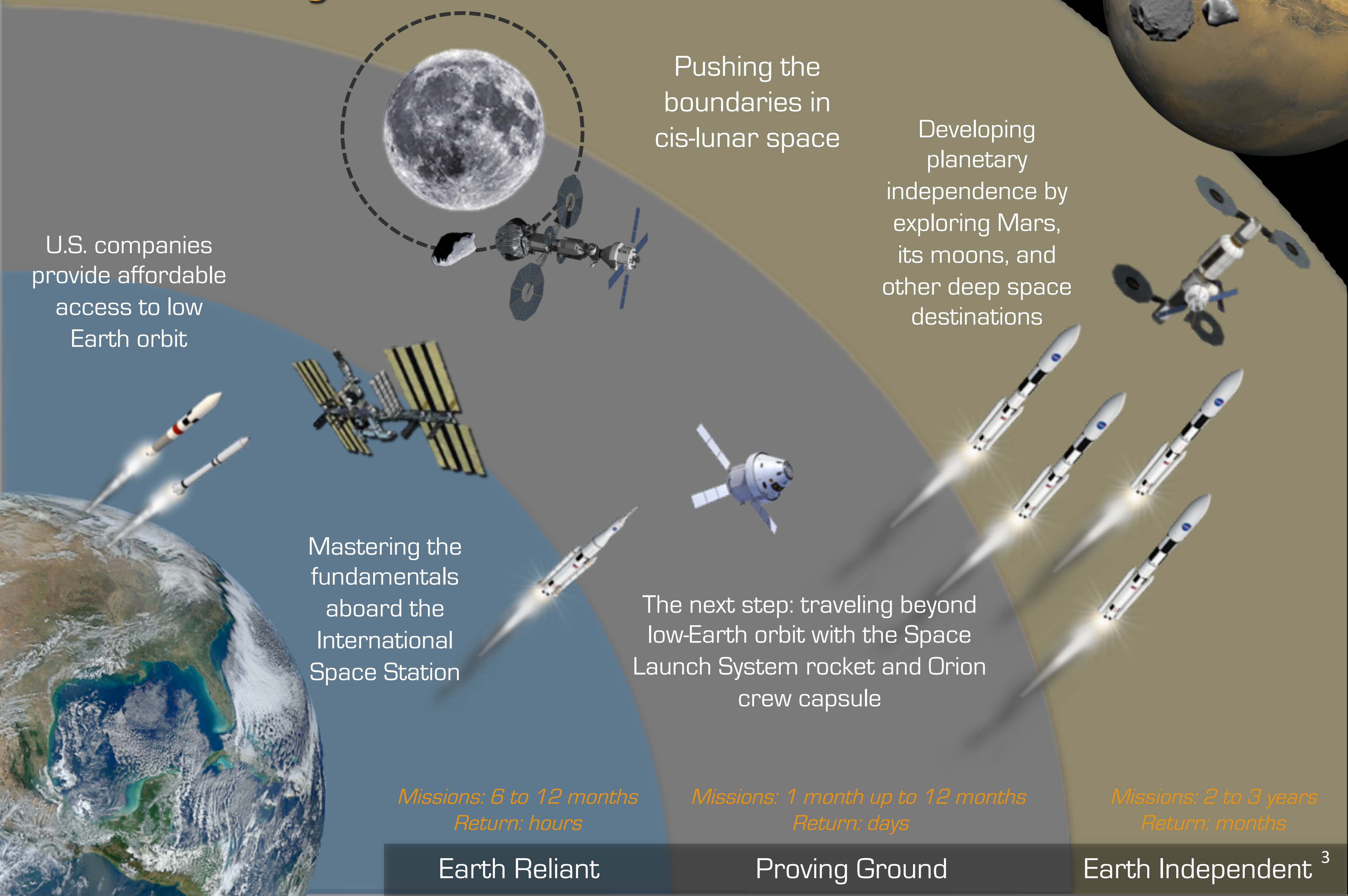
Critical for exploration beyond low Earth orbit

- Robotics & Automation
- Power Systems
- Propulsion
- Habitation & Life Support
- Space Resource Utilization



Sustainable Human Space Exploration

NASA's Building Blocks to Mars



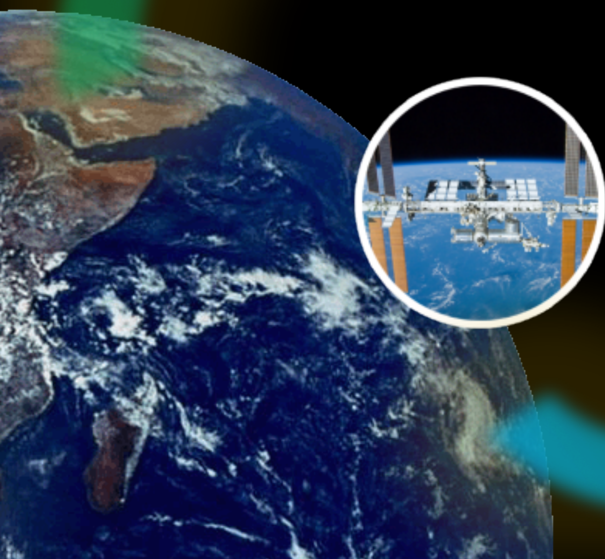
Evolvable Mars Campaign: Enabling Technologies

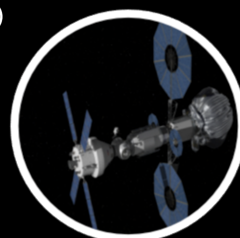
Transportation

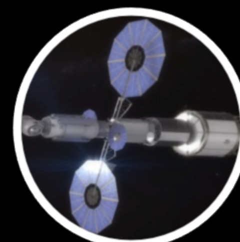
- Oxygen-Rich Staged Combustion (ORSC) Engine Technology
- Chem Prop (In-Space): LOX/Methane Cryo (Propulsion & RCS)
- Solar Electric Propulsion & Power Processing
- 10-100 kW Class Solar Arrays
- Cryo Propellant Acquisition & ZBO Storage
- AR&D, Prox Ops & Target Relative Navigation
- EDL, Precision Landing, Heat Shield
- Autonomous Vehicle Systems Management
- Mission Control Automation beyond LEO

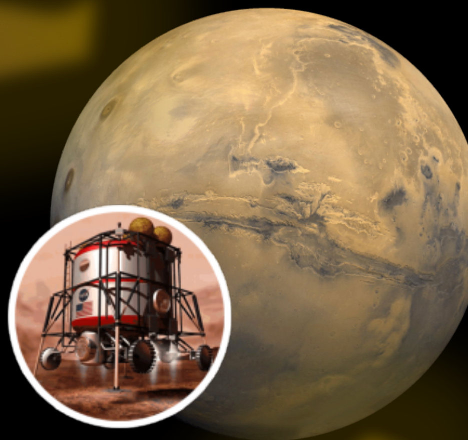
Staying Healthy

- Advanced, High-Reliability ECLSS
- Long-Duration Spaceflight Medical Care
- Long-Duration Spaceflight Behavioral Health & Performance
- μ-G Biomedical Counter-Measures for Long-Duration Spaceflight
- Deep Space Mission Human Factors & Habitability
- In-Flight Environmental Monitoring
- Human SPE & GCR Radiation Exposure Prevention & Protection
- Fire Prevention, Detection, Suppression (Reduced Pressure)









Working in Space

- Autonomy beyond LEO
- High Data Rate Forward Link Communications
- High-Rate, Adaptive, Internetworked Proximity Communications
- In-Space Timing & Navigation for Autonomy
- Fission Surface Power (FSP)
- **ISRU (Atmospheric & Regolith)**
- Mechanisms (low-temp), Dust Mitigation
- Tele-robotic Control of Robotic Systems with Time Delay
- Robots Working Side-By-Side with Suited Crew
- Robotics & Mobility **EVA Exploration Suit and PLSS**
- **Electro-Chemical Power Systems**
- **Advanced Fire Protection Systems**
- Deep Space Suit & Mars Surface Suit (EVA)
- Surface Mobility
- Suit Port, u-G tools & anchoring
- Advance Software Development/Tools

What are Space Resources?

- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments
- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - High Thermal Gradients
- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

Natural Space Resources

Four major resources on the Moon:

- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)
- Discarded materials: **Lander and crew trash and residuals**

~85% of Meteorites are Chondrites

Ordinary Chondrites 87%

FeO:Si = 0.1 to 0.5

Fe:Si = 0.5 to 0.8

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Trioilite - FeS

Source metals (Carbonyl)

Resources of Interest

- **Oxygen**
- **Water**
- Hydrogen
- Carbon/CO_2
- Nitrogen
- Metals
- Silicon

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal

Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles

Three major resources on Mars:

- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- **Water in soil**: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

Enstatite Chondrites 5%

Highly reduced; silicates contain almost no FeO

60 to 80% silicates; Enstatite & Na-rich plagioclase

20 to 25% Fe-Ni

Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)

Vision for Using Space Resources

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

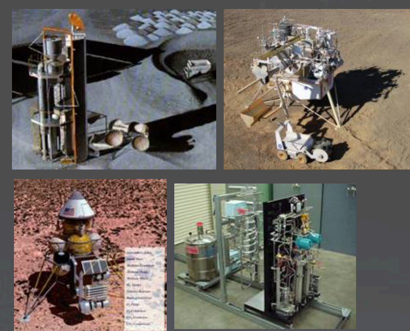
Resource Assessment (Prospecting)

Involves assessment of physical, mineral/ chemical, and volatile/ water resources, terrain, geology, and environment

Resource Acquisition

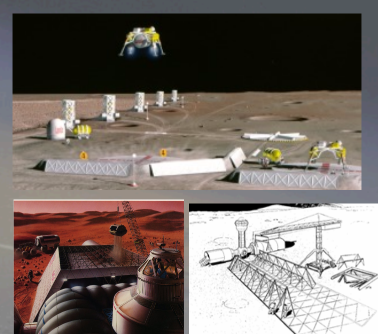
Involves extraction, excavation, transfer, and preparation before processing

Resource Processing/ Consumable Production



Involves multi-step thermal, chemical, and electrical processing of extracted resources into products with immediate use or as feedstock for construction and/or manufacturing

In Situ Construction

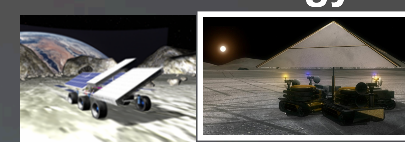


Involves processes and operations for civil engineering, infrastructure emplacement and structure construction using materials produced from in situ resources

In Situ Manufacturing

Involves production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

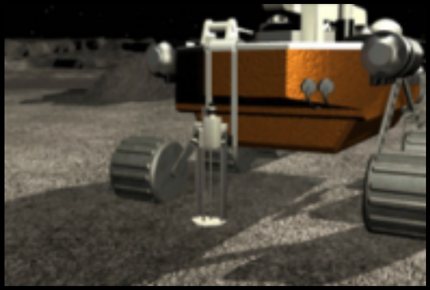
In Situ Energy



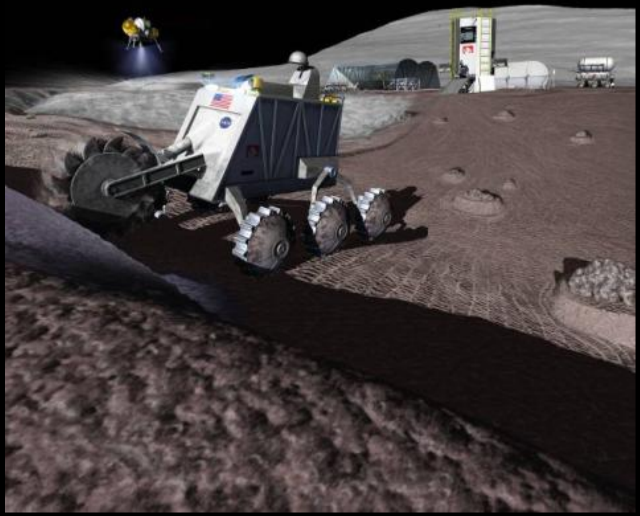
Involves creation and storage of electrical, thermal, and chemical energy from in situ derived resources

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, 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.

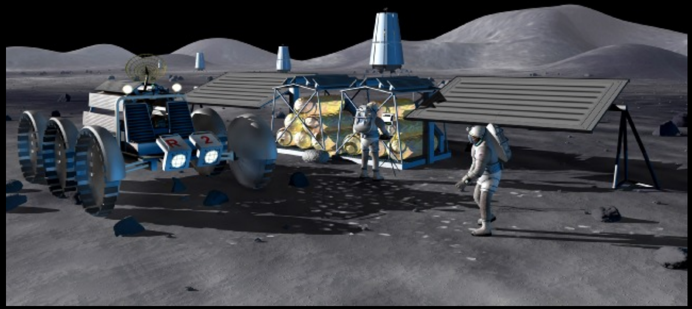
Potential Lunar ISRU Mission Capabilities



Excavation & Regolith Processing for O_2 and Metal Production

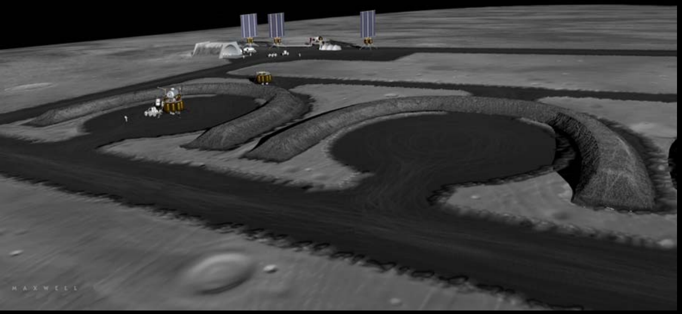


Consumable Depots and Waypoints for Crew & Power



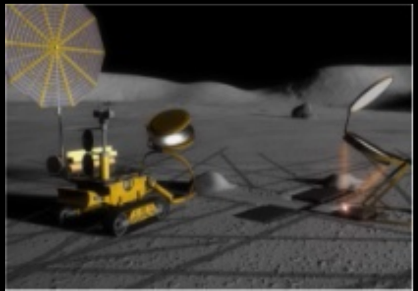
Polar Ice/Volatile Prospecting & Mining

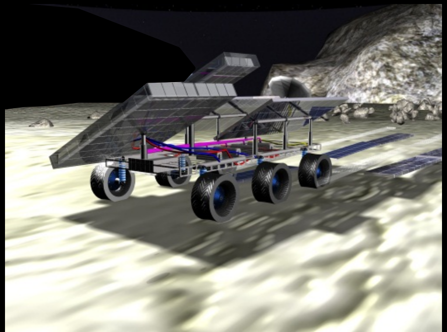
Structure and Habitat Construction

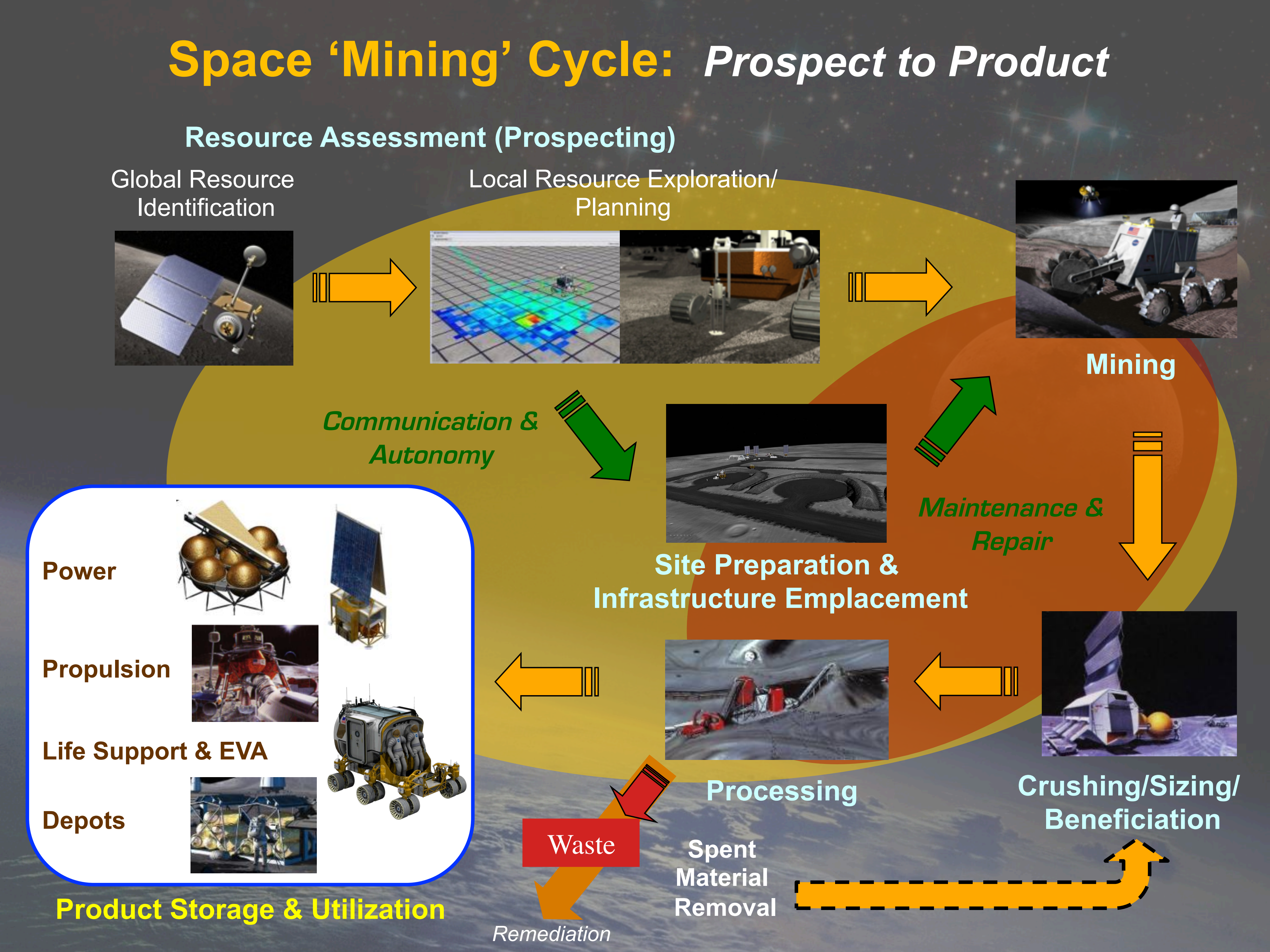


Landing Pads, Berm, and Road Construction

Solar and Thermal Energy Storage Construction






Space 'Mining' Cycle: Prospect to Product
Resource Assessment (Prospecting)
Global Resource Identification
Local Resource Exploration/ Planning
Mining
Communication & Autonomy
Maintenance & Repair
Site Preparation & Infrastructure Emplacement
Crushing/Sizing/ Beneficiation
Processing
Waste
Remediation
Spent Material Removal
Power
Propulsion
Life Support & EVA
Depots
Product Storage & Utilization

ISRU and Implementation into Human Mission Architectures

Development and Insertion of ISRU into Human Exploration Architectures is a function the expected Roles and Confidence of ISRU Capabilities and Products

- **Is ISRU a design driver for transportation, power, and habitation** or an eventual add on?
  - If Add-on: May require redesign and recertification of critical elements if not considered from the start
  - If Driver: May require reassessment of technology/capability selections for transportation, power, and life support. Will require early ground development and possible demonstration/pathfinder missions to build confidence

- **Is ISRU considered as an option for architecture issues and limitations?**
  - Radiation shielding, landing surface stability/plume damage, trash accumulation/ planetary protection, Earth launch and lander payload limitations, etc.

- **Is minimizing upfront development costs or long-term sustainability more important?**
  - ISRU will increase upfront costs for development and emplacement but will enable long-term sustainability through reduced number of launches, reduced logistics, and reusability

- **Is Commercialization of Space and insertion of commercial services into long-term exploration important?**
  - Government/ISRU for development/demonstration risk reduction and anchor tenant for products and services

The Enabling Role of ISRU in Human Exploration

- **Launch mass savings**: propellants, life support, parts for repairs and new hardware, energy generation
- **Reduce launch numbers**: risk/cost reduction
- **Mission life extensions**: local supply of critical consumables without waiting for new Earth supply, repairs with local materials, repurposing of end-of-life hardware
- **Ensure crew safety**: dissimilar redundancy for life support consumables, repairs, radiation shielding, increased independence for Earth logistics
- **Provide critical solutions for mission assurance**: safe landing zones preparation, extra propellant for return to Earth (leakage/storage failure), large-scale surface shielding
- **Relax critical requirements**: Propulsion Isp (ex. press-fed vs pump-fed), amount of closure of life support (ex. efficiency of water removal from brine)
- **Enable mission capabilities not possible or difficult without ISRU**: reusable landers and space transportation, surface hoppers, hydrocarbon-based fuel cells for surface mobility, trash disposal (propellants and planetary protection), extend duration of exploration activities in extreme environments
- **Enhance crew psychological health**: knowledge and tools for self-reliance and survival
- **Space commercialization**: Develop technology and reduce risk for space commercialization thereby reducing life cycle costs

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

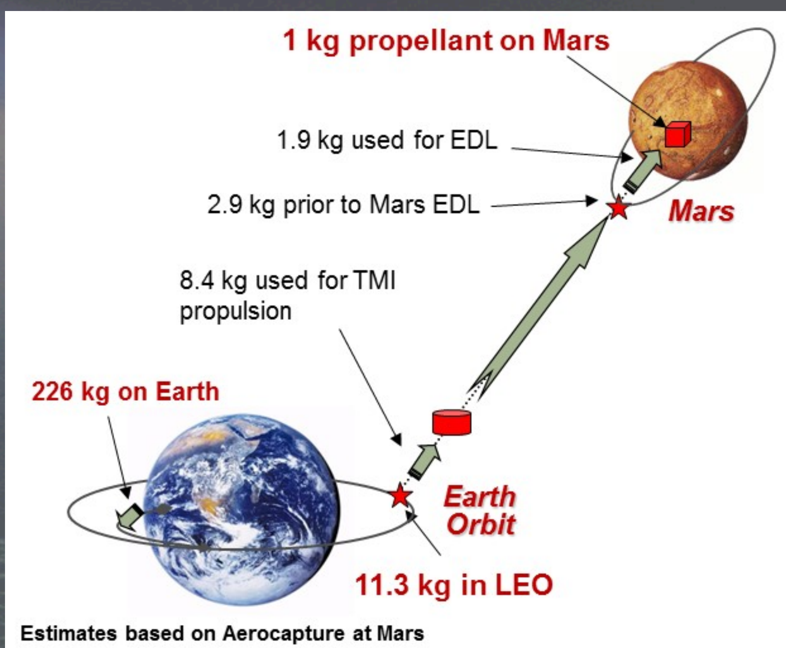
- Surface soil processing operations associated with ISRU applicable to Moon and Mars
- ISRU subsystems and technologies are applicable to multiple destinations and other applications
- Resource assessment for water/ice and minerals common to Moon, Mars, and NEOs

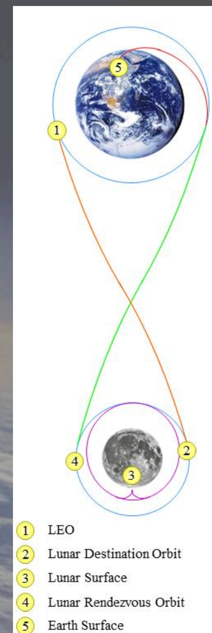
Leverage (Gear) ratios using ISRU

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent

- **Mars mission**
  - Oxygen only — 75% of ascent propellant mass; 20 to 23 mT
  - Methane + Oxygen — 100% of ascent propellant mass: 25.7 to 29.6 mT
    Regeneration of rover fuel cell reactant mass
- **Phobos mission**
  - Trash to O_2/CH_4 — 1000+ kg of propellant



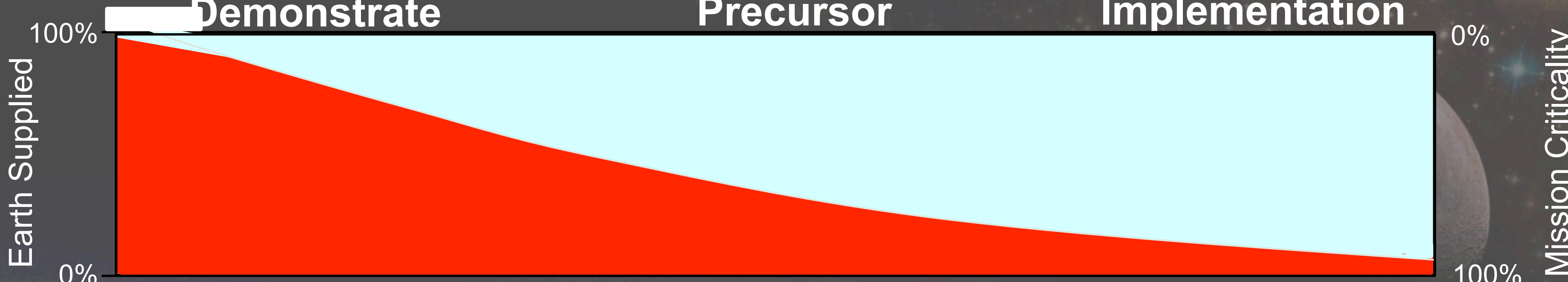


A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

Phased Approach to ISRU Architecture Incorporation

Utilize phased approach to incorporate ISRU with minimum risk to mission success

Resource Prospecting/ Demonstrate | **PILOT/Robotic Precursor** | **Utilize/Full Implementation**



Purpose

- Characterize local material/resources; evaluate terrain, geology, lighting, etc.
- Demonstrate critical technologies, functions, and operations
- Verify critical engineering design factors & environmental impacts
- Address unknowns or Earth based testing limitations (simulants, 1/6 g, contaminants, etc.)

Purpose

- Enhance or extend capabilities/ reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verity use of ISRU products

Purpose

- Enhance or enable new mission capabilities
- Reduce mission risk
- Increase payload & science capabilities

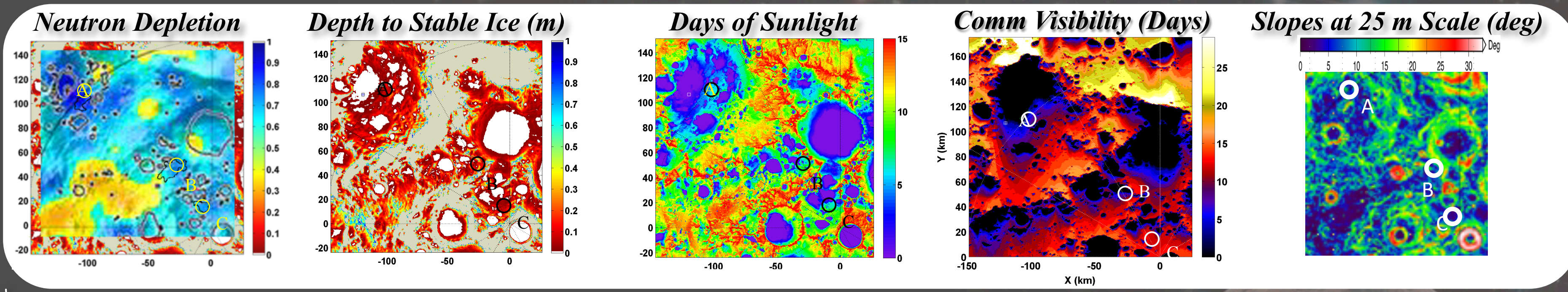
- **Resource Prospector**
- **Mars 2020**
- **Phobos Pathfinder**

- **Mars Surface Pathfinder**
- **Lunar short stay**

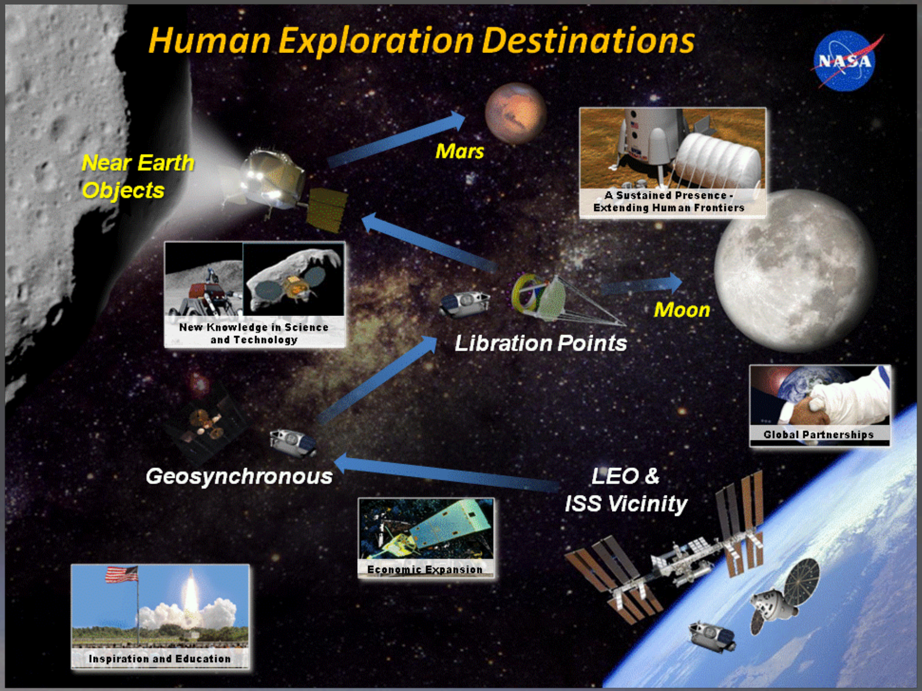
- **Mars DRA 5.0**
- **Lunar outpost**

Stepwise Approach to Utilizing Space Resources

Or mineral maps for oxygen/metals



Multiple Pathways to Mars



Moon Pathway

- **Use Moon as a Proving Ground for Mars Surface ISRU**
  - Regolith ice/water mining for consumables & propellants
  - Long-term operations in severe environment
  - Demonstrate common critical technologies with Mars
  - Trash processing to propellant/gas for humans in cis-lunar space
  - Demonstrate civil engineering
- **Use Moon Resources for Mars Exploration**
  - Surface & cis-lunar propellant depots
  - Reusable lander & space transportation elements
  - Civil engineering for landing pads, roads, emplacement
  - Commercial on-ramp for lunar ISRU products
- **Use Moon Resources to Stay**
  - Metal extraction and part fabrication
  - Surface construction
  - *In situ* Energy: thermal storage, cold crater heat sink

Cis-Lunar/NEA/Phobos Pathway

- **Use ISS, Cis-Lunar Space and Captured NEA as a Proving Ground for Phobos ISRU**
  - Trash processing to propellant/gas for humans in cis-lunar space
  - Micro-g ISRU for resource prospecting, acquisition, and processing for consumables and shielding
  - Demonstrate in-space manufacturing and construction with in situ derived resources
- **Use NEA/Phobos Resources for Mars Exploration**
  - NEA/Phobos material for shielding and construction
  - Cis-lunar and Phobos propellant depots
  - Reusable lander & space transportation elements
  - Commercial on-ramp for NEA ISRU products
- **Use Mars Resources for Initial Missions and to Stay**
  - Atm. CO_2 capture and processing (O_2, buffer gases)
  - Soil processing for water → Fuel production with CO_2
  - Civil engineering for landing and emplacement
  - Long-term: Soil processing for metals & plant growth; manufacturing and construction feedstock

Stepping Stone Approach for Demonstration & Utilization of Space Resources

Microgravity Processing & Mining

ISS & Space Habitats

ISRU Focus
- Trash Processing into propellants
- Micro-g processing evaluation
- In-situ fabrication

Purpose: Support subsequent robotic and human missions beyond Cis-Lunar Space

Near Earth Asteroids & Extinct Comets

ISRU Focus
- Micro-g excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- In-situ fabrication & repair
- Trash Processing

Purpose: Prepare for Phobos & future Space Mining of Resources for Earth

Phobos

ISRU Focus
- Micro-g excavation & transfer
- Water/ice and volatile prospecting & extraction

Purpose: Prepare for orbital depot around Mars

Planetary Surface Processing & Mining

Moon

ISRU Focus
- Regolith excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- Civil engineering and site construction

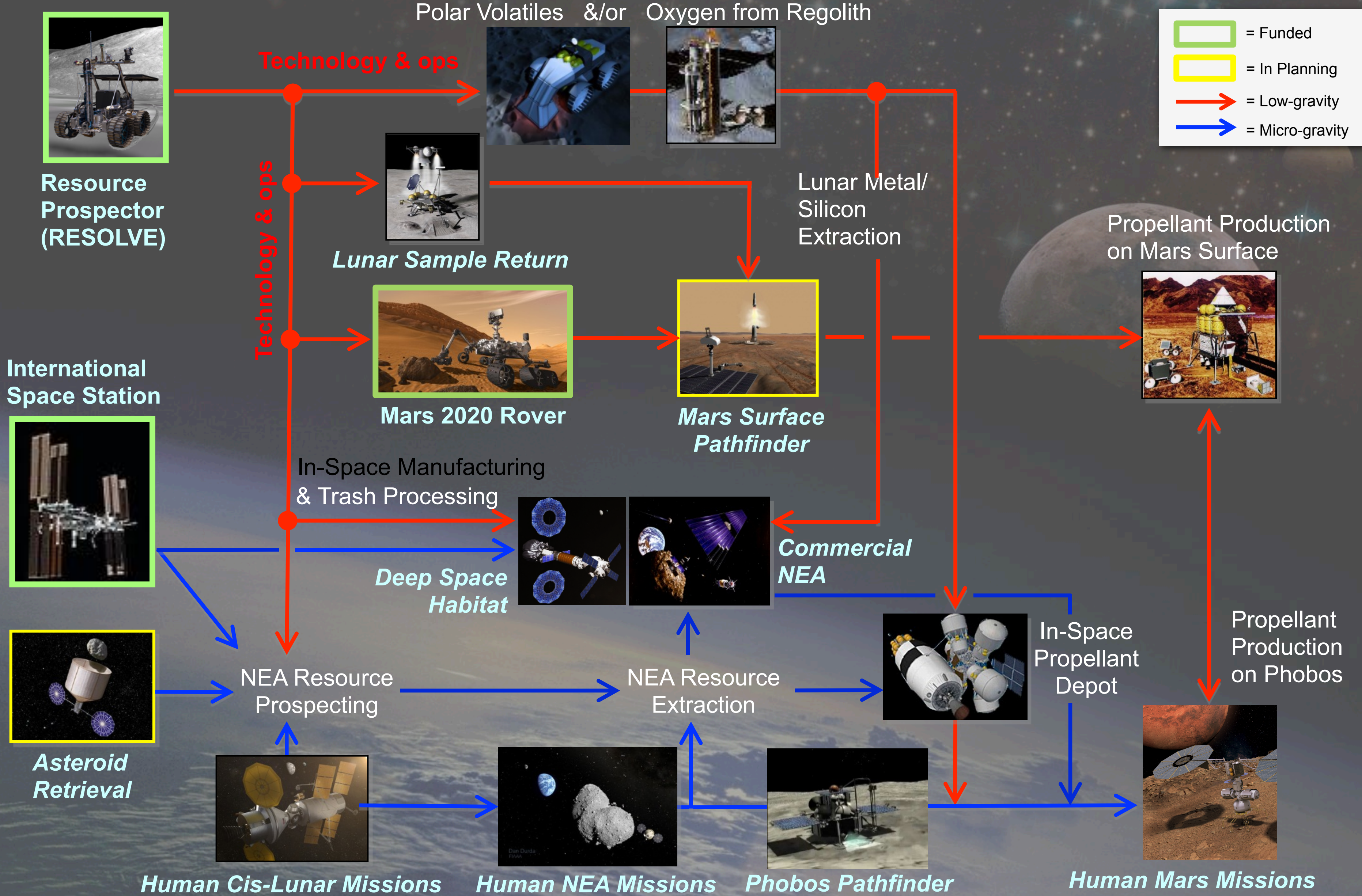
Purpose: Prepare for Mars and support Space Commercialization of Cis-Lunar Space

Mars

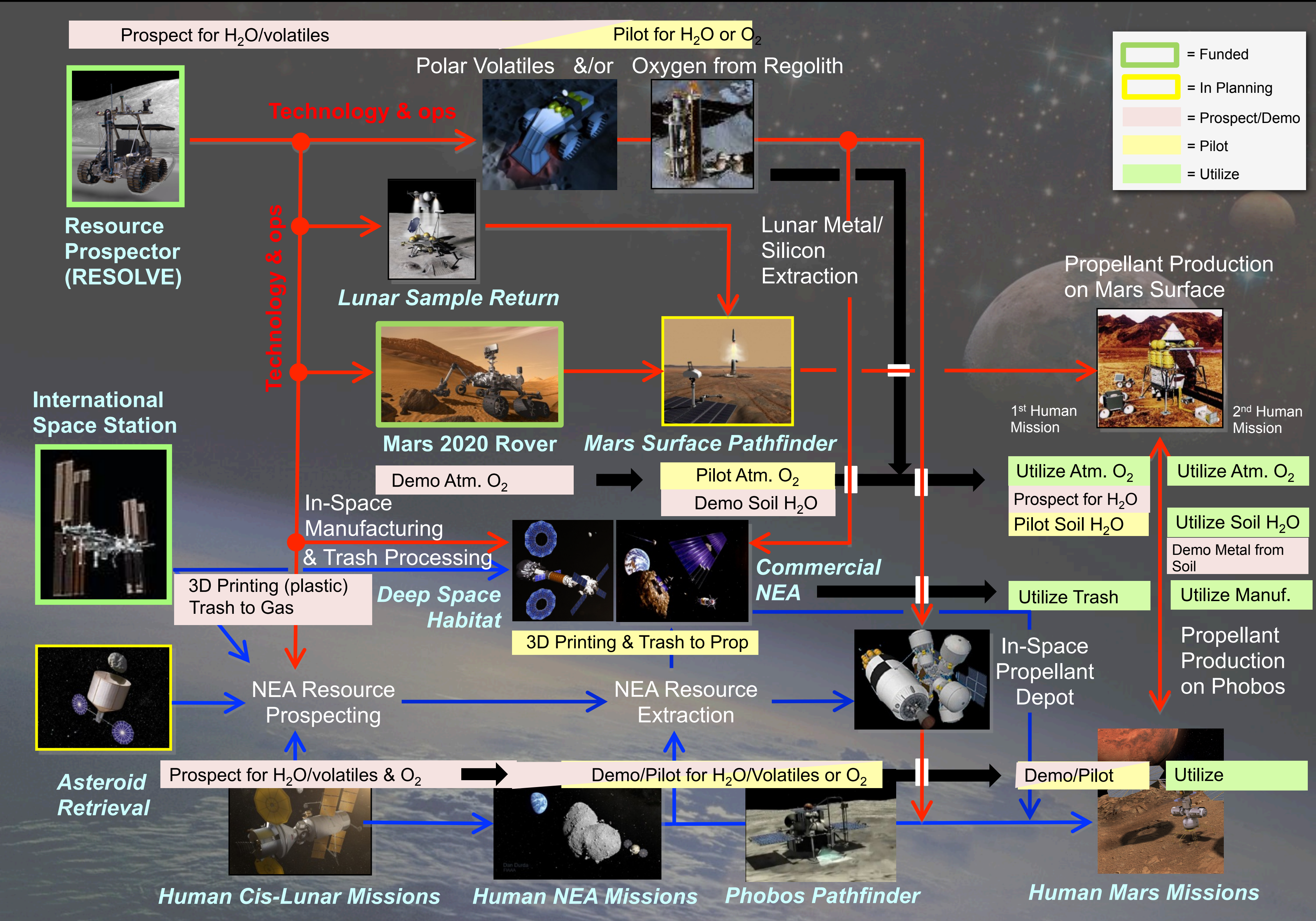
ISRU Focus
- Mars soil excavation & transfer
- Water prospecting & extraction
- Oxygen and fuel production for propulsion, fuel cell power, and life support backup
- Manufacturing & Repair

Purpose: Prepare for human Mars missions

Notional ISRU Mission Evolution To Support Multiple Pathways to Mars Surface



Notional ISRU Mission Evolution – With Phased Implementation

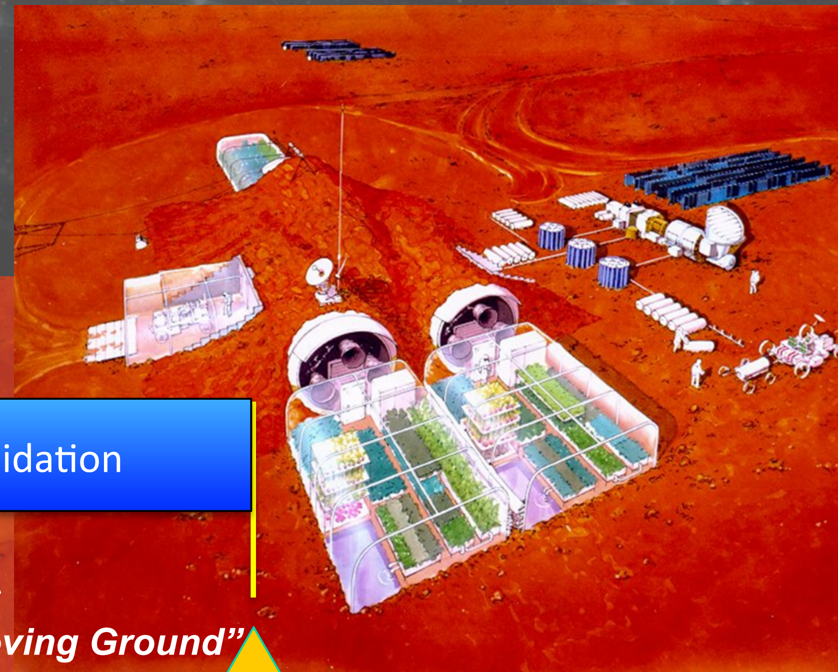


Architecture Approach within the Evolvable Mars Campaign – Mars Surface

Emplacement

(Threshold Goal) 12-18 month stay enabled
Earth independent for that time period

1



Consolidation

EMC
“Mars Surface Proving Ground”

2

(Ultimate Goal) Indefinite stay enabled
Earth independent

Utilization

Phase 1 | Phase 2 | Phase 3

A <u>two-major-milestone</u>, <u>three-phase</u> surface architecture approach is used to achieve the Question A-Prime Ultimate Goal (i.e., Earth Independence), and would include a “Mars Surface Proving Ground” during Phase 2

ISRU Implementation for Mars Surface –
Mission Phases

Pioneering & Emplacement

- **Baseline**
  - O_2 production for Mars Ascent Vehicle (MAV) and life support
- **Should be baselined for 1st mission:**
  - Resource exploration & prospecting (surveying, mapping, subsurface sampling & characterization)
  - Trash processing (once crew arrives) for propellant
- **Options for 1st mission**
  - Terrain shaping (leveling, consolidation, berm building, site surveying, surface assets protection, etc..)
  - Water extraction from soil for life support, MAV propulsion, and fuel cell reactants
  - Nitrogen for habitats
  - Landing zone construction
  - Repurposing

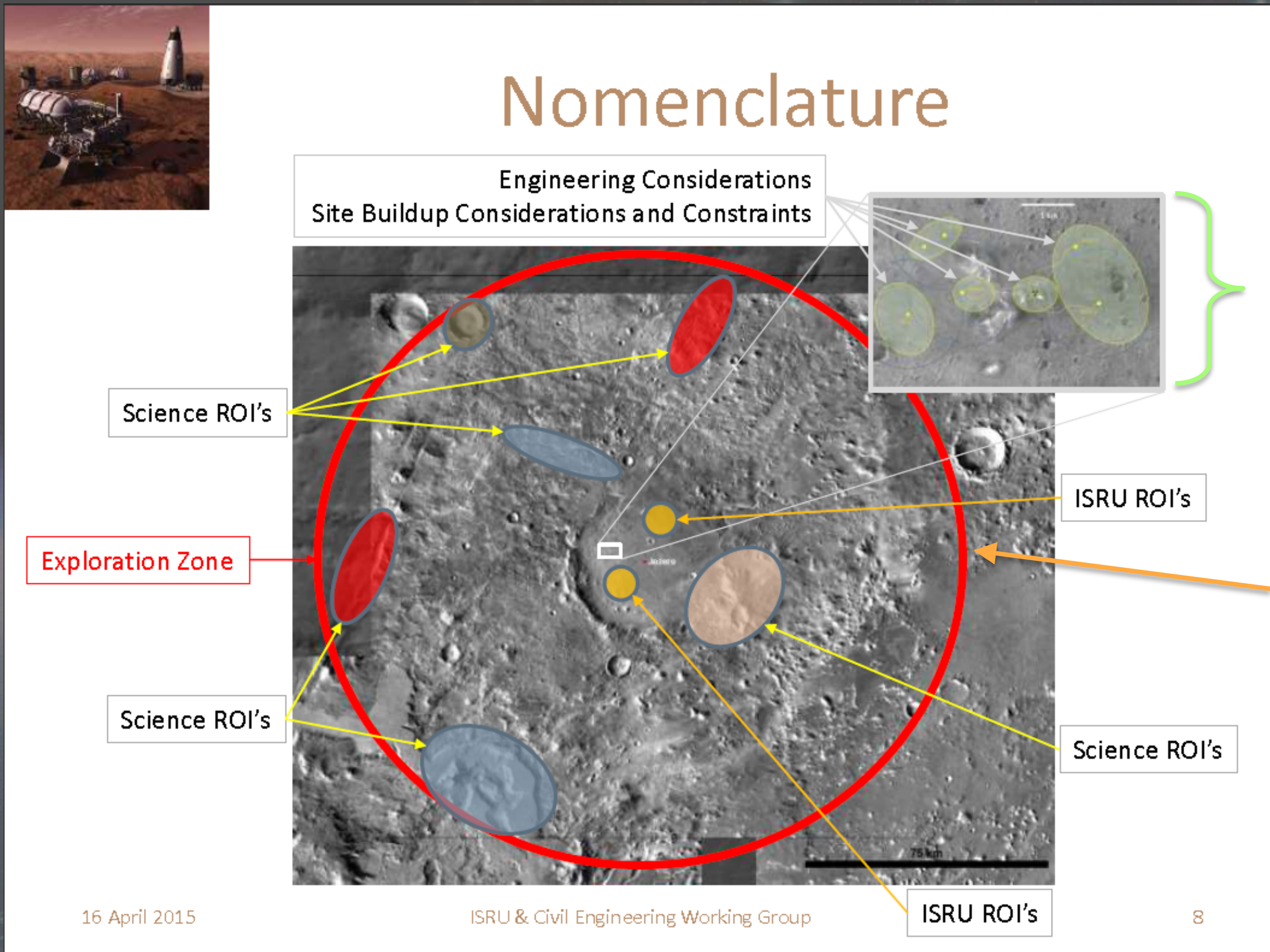
Consolidation

- **ISRU support of Mars Field Station capabilities**
  - Extended range resource exploration & prospecting
  - O_2, H_2O, and CH_4 production for life support, propulsion, & fuel cells
  - Trash processing for propellant and planetary protection
  - Scientific exploration support (trenching to expose subsurface features, subsurface instruments emplacement)
  - Landing zone construction
  - Establish consumable fluid depot; transfer capabilities for O_2, CH_4, & H_2O
- **Demonstrate capabilities for Utilization**
  - Cleaning products for science and planetary protection
  - Gases for purging systems, esp. dormant hardware
  - Metals production for parts manufacturing
  - Additive 3D regolith constructions
  - Plastic production with ISRU products
  - Nutrient/food production with ISRU products

Utilization

- **All Consolidation Capabilities**
- **New Capabilities**
  - Reusable landers and/or ascent vehicles
  - Hopper propellants and extended range consumables
  - Metals production for parts manufacturing
  - Structure and habitat construction
  - Plant growth with ISRU: soils, water, nutrients
  - Additive 3D Regolith constructions
  - Transformation of end-of-life hardware (other than repurposing):

Mars Landing Site – Human Exploration



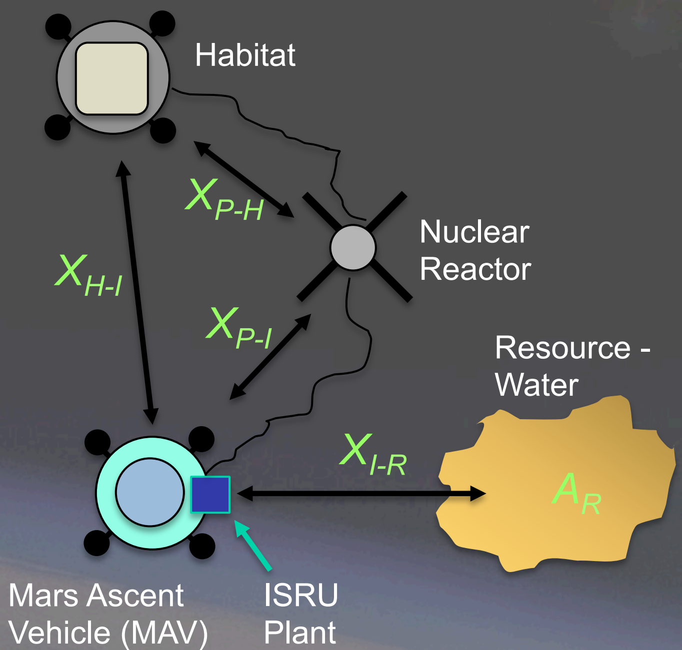
Mission Phase

Pioneering,
Emplacement,
& Consolidation

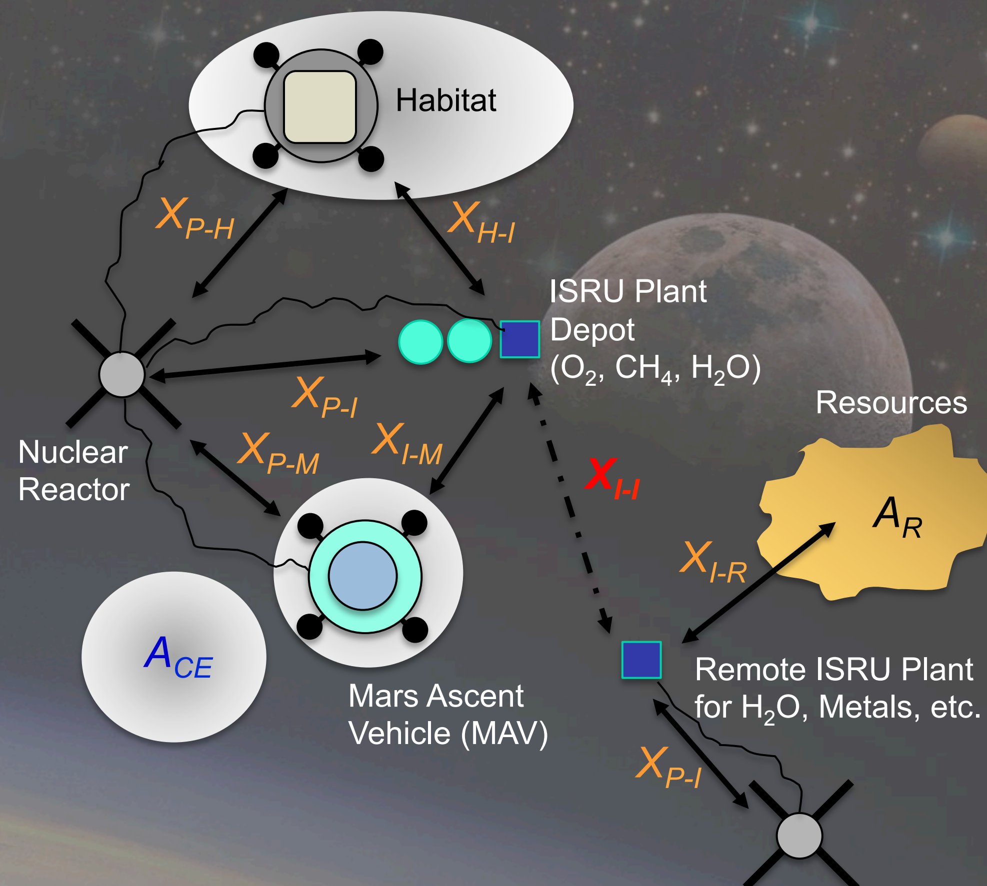
Utilization & Earth
Independence

Mars Surface Infrastructure and ISRU

Emplacement Phase



Consolidation or Utilization Phase



X_{H-I} = distance between Habitat and ISRU Plant

X_{P-I} = distance between Power and ISRU Plant

X_{P-H} = distance between Power and Habitat

X_{I-R} = distance between ISRU Plant and Resource

A_R = Area of Resource

X_{I-M} = distance between ISRU Plant and MAV

X_{I-I} = distance between ISRU Plants

A_R = Area of Civil Engineering

ISRU Site Selection Engineering Guidelines (1)

ISRU and Infrastructure

- Availability and placement of power: nuclear reactor (X_{P-I})
- ISRU Connection to Mars Ascent Vehicle (MAV) (X_{M-I}):

Terrain

- At area of resource of interest (A_R):
- Between area of resource and ISRU processing and product storage systems (X_{I-R})
- Around infrastructure (A_{CE}) and ISRU processing/storage systems (X_{H-I}, X_{M-I})

Access to Water and Mineral Resources

- For Emplacement Phase: use in human missions (first 3 missions) X_{I-R} and A_R
- For evaluation of water extraction methods for future site selection or expanded/ sustained human surface operations (X_{I-I})
- For evaluation of mineral resources for future site selection

Civil Engineering and Site Construction

- Natural Features Preferential for Civil Engineering
- Natural features for Radiation Production
- Natural features for Infrastructure Emplacement and Road/Landing Pads
- Features and resources for Construction

ISRU Site Selection Engineering Guidelines (2)

Environmental Guidelines

- Altitude on Mars Surface:
- Sunlight:
- Wind
- Communications
- Temperatures and Temperature Extremes
- Special Regions
  - Cat IV (c) Special Regions (COSPAR) must be avoided

Lunar and Space Exploration Vision for Space Resource Utilization

- Affordable and Sustainable Human Exploration requires the development and utilization of space resources

- The search for potential resources (Prospecting) and the production of mission critical consumables (propellants, power reactants, and life support gases) is the primary focus of NASA technology and system development since they provide the greatest initial reduction in mission mass, cost, and risk.

- There are multiple pathways to Mars
  - Identification and Selection of common technologies and processes for multiple destinations is critical
  - Terrestrial and commercial involvement is important to reduce long-term costs and risks

- Plans for developing ISRU through an evolution of missions starting with the lunar Resource Prospector Mission and Asteroid Retrieval Mission has been proposed to minimize risk
  - Several missions in this evolutionary plan have been initiated or are in the planning stage

Questions?

Space Resources Utilization Changes How We Can Explore Space

Mass Reduction

- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon or Mars
- Chemical propellant is the largest fraction of spacecraft mass

Cost Reduction

- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

Space Resource Utilization

Risk Reduction & Flexibility

- Number of launches & mission operations reduced
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- Radiation & landing/ascent plume shielding
- Reduces dependence on Earth

Expands Human Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

Solves Terrestrial Challenges & Enables Space Commercialization

- Develops alternative & renewable energy technologies
- New renewable construction
- CO_2 remediation
- Green metal production

- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

Moon, Mars, & Near Earth Objects (NEOs)

	Moon	Mars	NEOs
Gravity	1/6 g	3/8 g	Micro-g
Temperature (Max) (Min.) (Min. Shade)	110 °C/230 °F -170 °C/-274 °F -233 °C/-387.4 °F	20 °C/68 °F -140 °C/-220 °F	110 °C/230 °F -170 °C/-274 °F -233 °C/-387.4 °F
Solar Flux	1352 W/m^2	590 W/m^2	Varied based on distance from Sun
Day/Night Cycle	28+ Days - Equator Near Continuous Light or Dark - Poles	24.66 hrs	Varied - hrs
Surface Pressure	$1x10^{-12}$ torr	7.5 torr	$1x10^{-12}$ torr
Atmosphere	No	Yes CO_2, N_2, Ar, O_2	No
Soil	Granular	Granular & clay; low hydration to ice	Varied based on NEO type
Resources	Regolith (metals, O_2) H_2O/Volatile Icy Soils	Atmosphere (CO_2) Hydrated Soils	Regolith (metals, O_2) Hydrated Soils H_2O/Volatile Icy Soils

- **The Moon has aspects in common with Mars and NEOs/Phobos**
- **All destinations share common technologies, processes, and operations**
- **NEO micro-gravity environment is the largest difference between destinations**

Space Resources Challenges

- **What resources exist that can be used?**
  - Oxygen and metals from regolith/soils
  - Water/Ice
  - Atmospheres & volatiles
  - Thermal environments
  - Sunlight
  - Shielding: Lava tubes, regolith, water, hills/craters
- **What are the Uncertainties associated with the Resources?**
  - Polar volatiles:
    - **Where is it**, What is there, how is it distributed, terrain and environment, contaminants?
  - Mars water/ice in soil
    - What form is the water (ice, mineral-bound), how is it distributed, terrain and environment, contaminants?
  - Near Earth Objects/Asteroids/Mars Moons
    - What is there, how is it distributed, environment, contaminants
    - Ability to revisit NEO of interest (time between missions)
    - What techniques are required for micro-g mining and material processing?
- **Planetary Protection - Mars**
  - Forward contamination prevention
  - Preventing creation of 'Special Regions' during extraction and processing to extract water

❖ Good simulants are needed for development

ISRU Technical Challenges

- **Is it Technically feasible to collect, extract, and process the Resource?**
  - Energy: Amount and type (especially for polar resources in shadowed regions)
  - Life, maintenance, performance
  - Amount of new technology required

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery
  - No crew for maintenance; Non-continuous monitoring from Earth

- **High reliability and minimum (zero) maintenance**
  - No (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Develop highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Develop highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)

- **Operation in severe environments**
  - Efficient excavation of resources in dusty/abrasive environments
  - Methods to mitigate dust/filtration for Mars atmospheric processing
  - Micro-g environment for asteroids and Phobos/Deimos

- **Integration and Operation with other Exploration Systems**
  - Exploration systems must be designed to utilize ISRU provided products; may cause selection of different technologies/approaches

ISRU Development Areas vs Mission Applications

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Regolith-Soil Extraction					
Regolith (granular) Excavation & Transfer	X		X	X	
Hard Material Excavation & Transfer	P			P	P
Hydrated Soil /Material Excavation & Transfer	P		X	X	X
Icy-Soil Excavation & Transfer	X		X	X	
Resource Characterization					
Physical Property Evaluation	X				
Mineral/Chemical Evaluation	X			X	
Volatile-Product Analysis	X	X			X
Regolith-Soil Processing (Volatiles, O_2, Metal)					
Crushing			P	X	P
Size Sorting				P	
Beneficiation/Mineral Seperation				P	
Solid/Gas Processing Reactor	X		X	X	X
Solid/Liquid Processing Reactor				P	
Contaminant Removal			X	X	X

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Gas Processing					
Dust/Particle Filtration		X	X	X	X
CO_2 Capture - Separation		X		P	X
CO_2 Conversion into CO-O_2		P			
CO/CO_2 Conversion into H_2O-CH_4		P		P	X
H_2-CH_4 Separation		P		P	X
Water Processing					
Water Capture	X		X	X	X
Water Cleaup - Purity Measurment			X	X	X
Water Electrolysis		P	X	P	X
Regenerative Dryers		P	X	P	X
Support Systems					
Extended Operation Power Systems			P	P	
Extended Operation Thermal Systems			P	P	
Cryogenic Liquefaction, Storage, and Transfer					

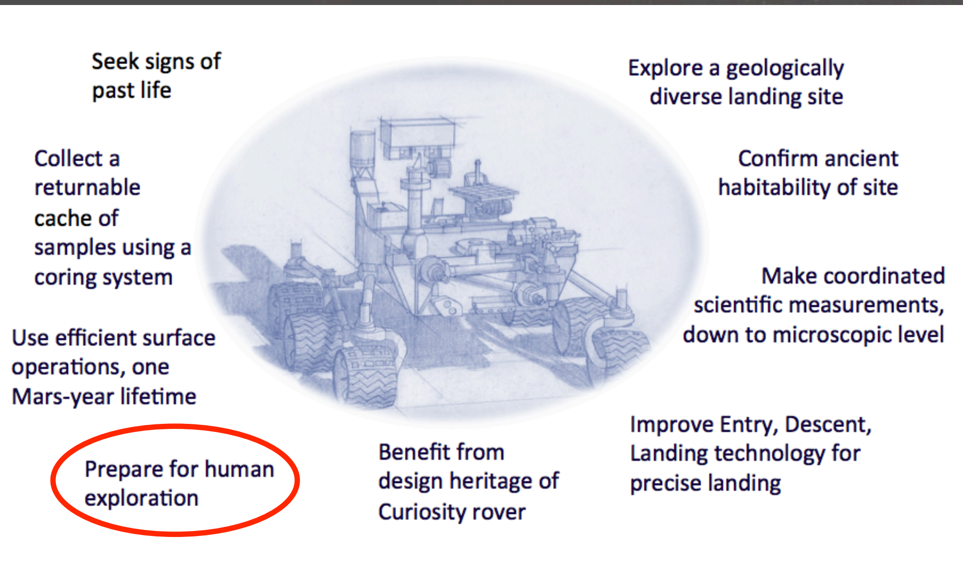
P = Possible need

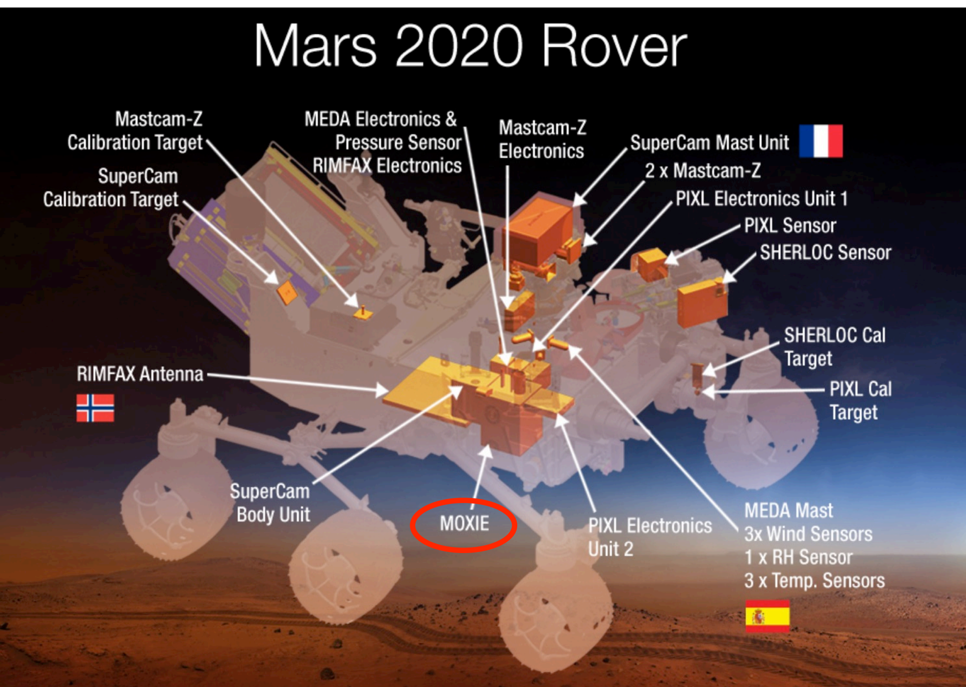
Main Discriminators: material (physical, mineral) water content/form (ice, hydration, surface tension), gravity (micro, low), pressure, (vacuum, atm.), and weathering

Implementation Strategy for Space Resource Utilization

- **ISRU implementation is phased to minimize risk to human exploration plans**
  - **Prospect and Demonstrate** – *Mission Feasibility*
    - Evaluate potential exploration sites: terrain, **geology/resources**, lighting, etc.
    - Demonstrate critical technologies, functions, and operations
    - Evaluate environmental impacts and long-term operation on hardware: dusty/abrasive/electrostatic regolith, radiation/solar wind, day/night cycles, polar shadowing, etc.
  - **Pilot Scale Demonstration** – *Mission Enhancement*
    - Perform critical demonstrations at scale and duration to minimize risk of utilization
    - Obtain design and flight experience before finalizing human mission element design
    - Pre-deploy and produce product before crewed missions arrive to enhance mission capability
  - **Utilization Operations** – *Mission Enabling*
    - Produce at scale to enable ISRU-fueled reusable landers and support extended duration human surface operations (mobility, manufacturing, construction, food, etc.)
    - Commercial involvement or products bought commercially based on previous mission results
- **Identify technologies and systems for multiple applications (ISRU, life support, power) and multiple mission (Moon, Mars, NEOs)**
- **Multinational (government, industry, and academia) involvement for development and implementation leading to space commercialization**

MOXIE - Mars Oxygen ISRU Experiment





Purpose

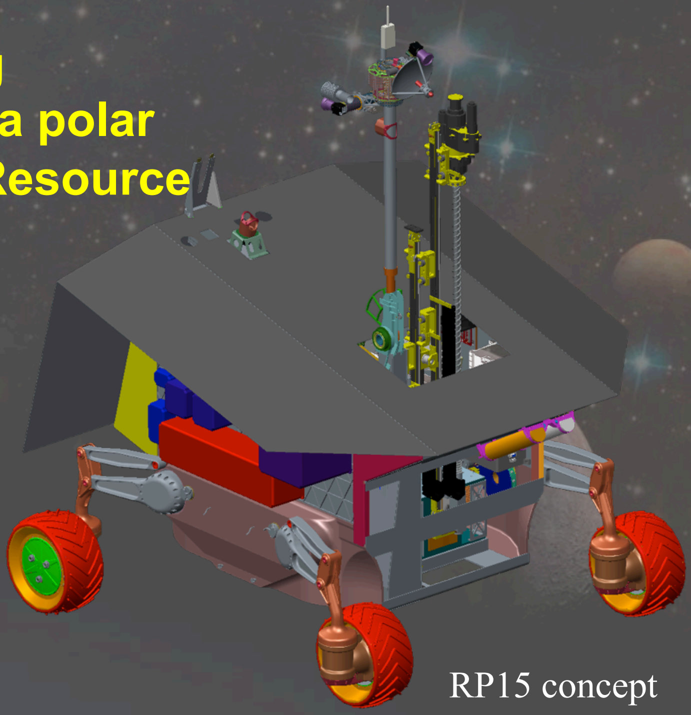
- Verification of >99.6% pure O_2 at >20 g/hr
- Key process variables that allow us to:
  - Optimize the production process
  - Inform future design

Demonstration Parameters

- Mass: 8.1 kg
- Max Power: **53/218 W** (CAC/generation)
- Volume: 23.9 x 23.9 x 30.9 cm
- O_2 Production Rate: **22 g/hr**
- CO_2 Feed Rate: 0.026 g/s
- # SOXE stacks: 2
- Cells per Stack: 11
- Active Cell Area: 12 cm^2
- Operating Temp: 800 °C
- Mass: **9.7 kg (MEV)**
- Max Power: 244 W (MEV)
- Data Volume: 1.3 MB per compression/ generation cycle
- Compression time: 3 hr cumulative (flexible timing)
- O_2 generation time: 30 minutes
- Control: Multi-variable process control & monitoring
- Dust Imaging: <10µ resolution

Resource Prospector - RESOLVE

The Resource Prospector Mission (RPM) is being developed to prospect for volatiles (water ice) in a polar region of the Moon, and demonstrate an In-Situ Resource Utilization (ISRU) capability.



RP15 concept

- **The RP Project is working two mission angles in FY15:**
  - **"RP20":** Phase A partner development for 2020 flight project
  - **"RP15":** FY15 "Mission-in-a-year" build of an integrated rover/payload system to mature designs and retire mission risk