System Maturation Team (SMT) Assessment of In Situ Resource Utilization (ISRU) for NASA's Evolvable Mars Campaign (EMC)

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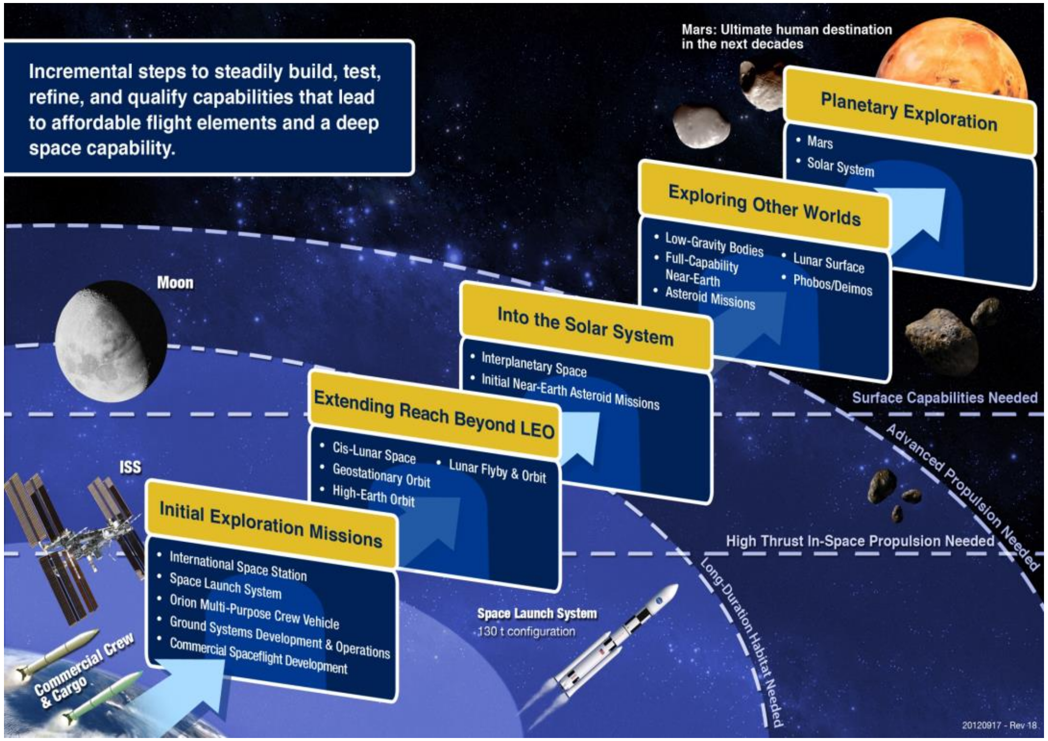
NASA's Capability-Driven Framework (CDF) for Human Spaceflight Exploration

NASA established the Human Exploration Framework Team (HEFT) in 2010 to analyze exploration and technology concepts and provide inputs to the agency's senior leadership on the key components of a safe, sustainable, affordable and credible future human space exploration endeavor.

This study determined that the most robust path for NASA in human space flight is a *capability-driven framework (CDF) approach,* where evolving capabilities would enable increasingly complex human exploration missions over time.

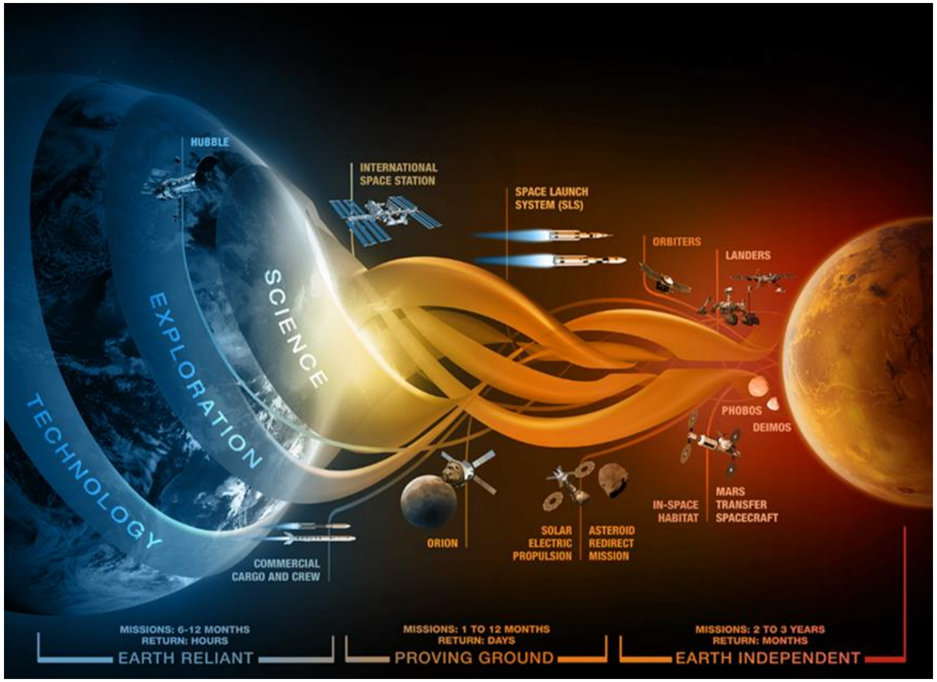


NASA 2014 Strategic Plan

Objective Strategy:

Charting the Course for Sustainable Human Space Exploration outlines NASA's strategy for human exploration in deep space.

- First, it is *capability-driven*. Each capability provides a specific *function that solves an exploration challenge, and in combination with other capabilities*, it will advance human presence into our solar system.
- Second, it is *multi-destination*. Rather than creating specialized, destination-specific hardware, this provides *adequate flexibility to carry out increasingly complex missions to a range of destinations over time*.

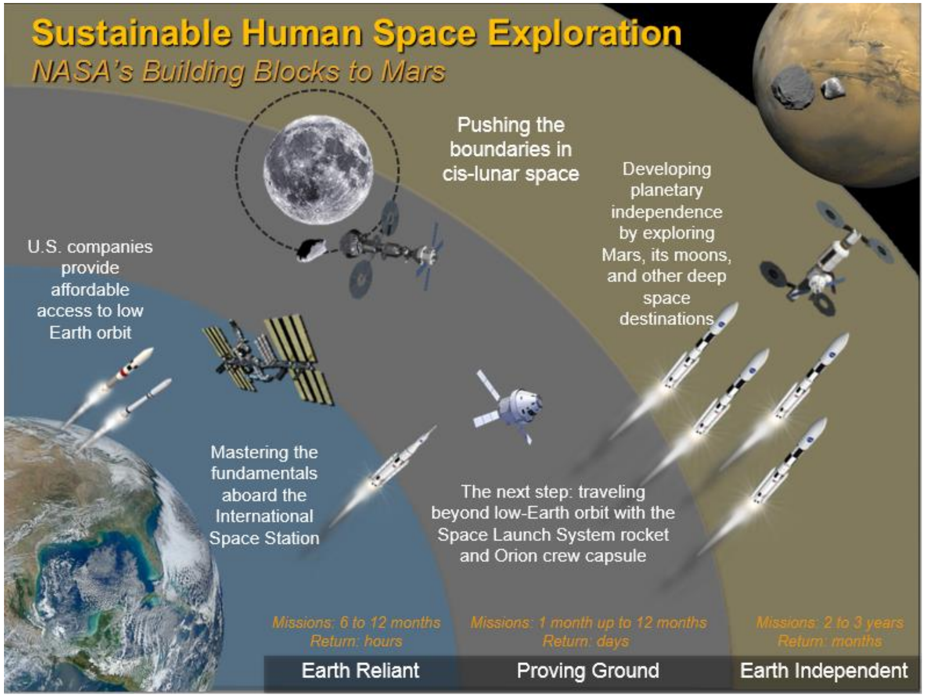


NASA is developing *a core set of evolving capabilities to ensure that the Nation's space program is robust, sustainable, and flexible*.

Evolvable Mars Campaign (EMC) Study

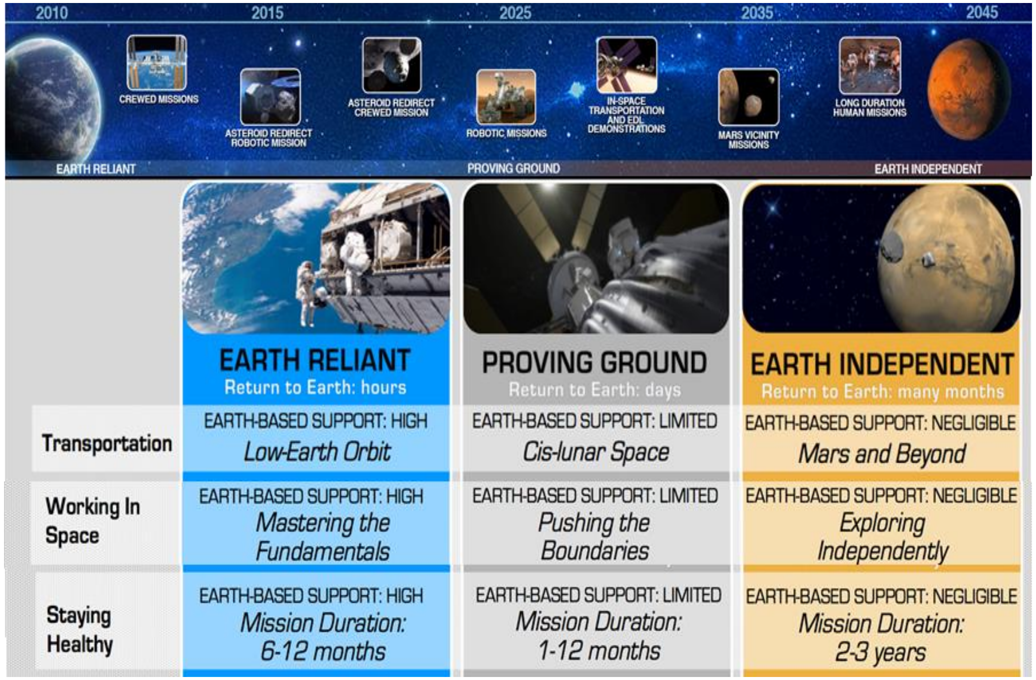
The EMC follows three primary phases of missions consistent with the Pioneering Space strategy. These phases consist of missions with increasing duration and complexity, and greater capability.

- The initial phase, “**Earth Reliant**” consists of mission durations of 6 to 12 months with a return to Earth accomplished within hours.
- The second phase, the **Proving Ground**, includes mission durations of 1 to 12 months that require days for Earth return (for example, missions in cislunar space). It is expected that primary demonstration, testing, and validation of Mars-required capabilities would be accomplished within deep space during this second phase.
- The third and final phase, “**Earth Independent**” includes mission durations on the order of two to three years and Earth return requiring months.



The EMC outlines a cadence of missions that align with the CDF and the pioneering space strategy.

- The EMC describes an exploration path that follows incremental steps to build, test, refine, and qualify critical capabilities, eventually enabling crewed planetary exploration to the surface of Mars.
- The capabilities needed to address the Mars challenges are identified and categorized into the following focus areas:
  - Transportation (Crew and Cargo to and from Deep Space, and In-Space)
  - Staying Healthy (Short and Long Duration Habitation, EVA, and Crew Health)
  - Working in Space (Destination Systems)
- The EMC also identifies capability performance metrics for architecture elements across multiple destinations within these areas.
- The evolvable nature of the EMC allows NASA to invest in critical capabilities to enable near term missions, while still making progress toward human missions to Mars.



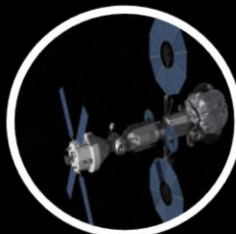
Evolvable Mars Campaign: Enabling Technologies

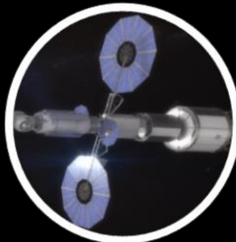
Transportation

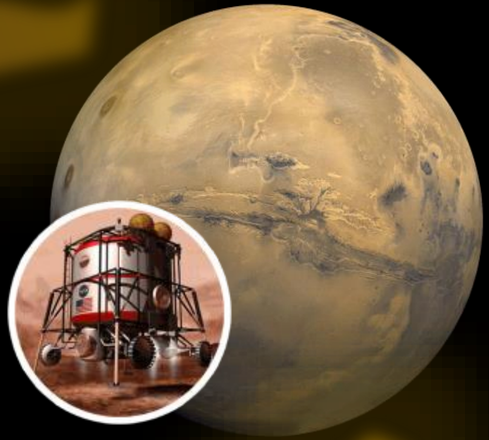
- Oxygen-Rich Staged Combustion (ORSC) Engine Technology
- Chem Prop (In-Space): LOX/Methane Cryo (Propulsion & RCS)
- Solar Electric Propulsion & Power Processing
- 10-100 kW Class Solar Arrays
- Cryo Propellant Acquisition & ZBO Storage
- AR&D, Prox Ops & Target Relative Navigation
- EDL, Precision 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
- m-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

System Maturation Teams - Integrated capability investment decisions with traceability to human exploration needs

System Maturation Team
Autonomous Mission Operations (AMO)
Communication and Navigation (Comm/Nav)
Crew Health & Protection and Radiation (CHP)
Environmental Control and Life Support Systems and Environmental Monitoring (ECLSS-EM)
Entry, Descent and Landing (EDL)
Extra-vehicle Activity (EVA)
Fire Safety
Human-Robotic Mission Operations
In-Situ Resource Utilization (ISRU)
Power and Energy Storage
Propulsion
Thermal (including cryo)
Discipline Team - Crosscutting
Avionics
Structures, Mechanisms, Materials and Processes (SMMP)
Dormancy Operations

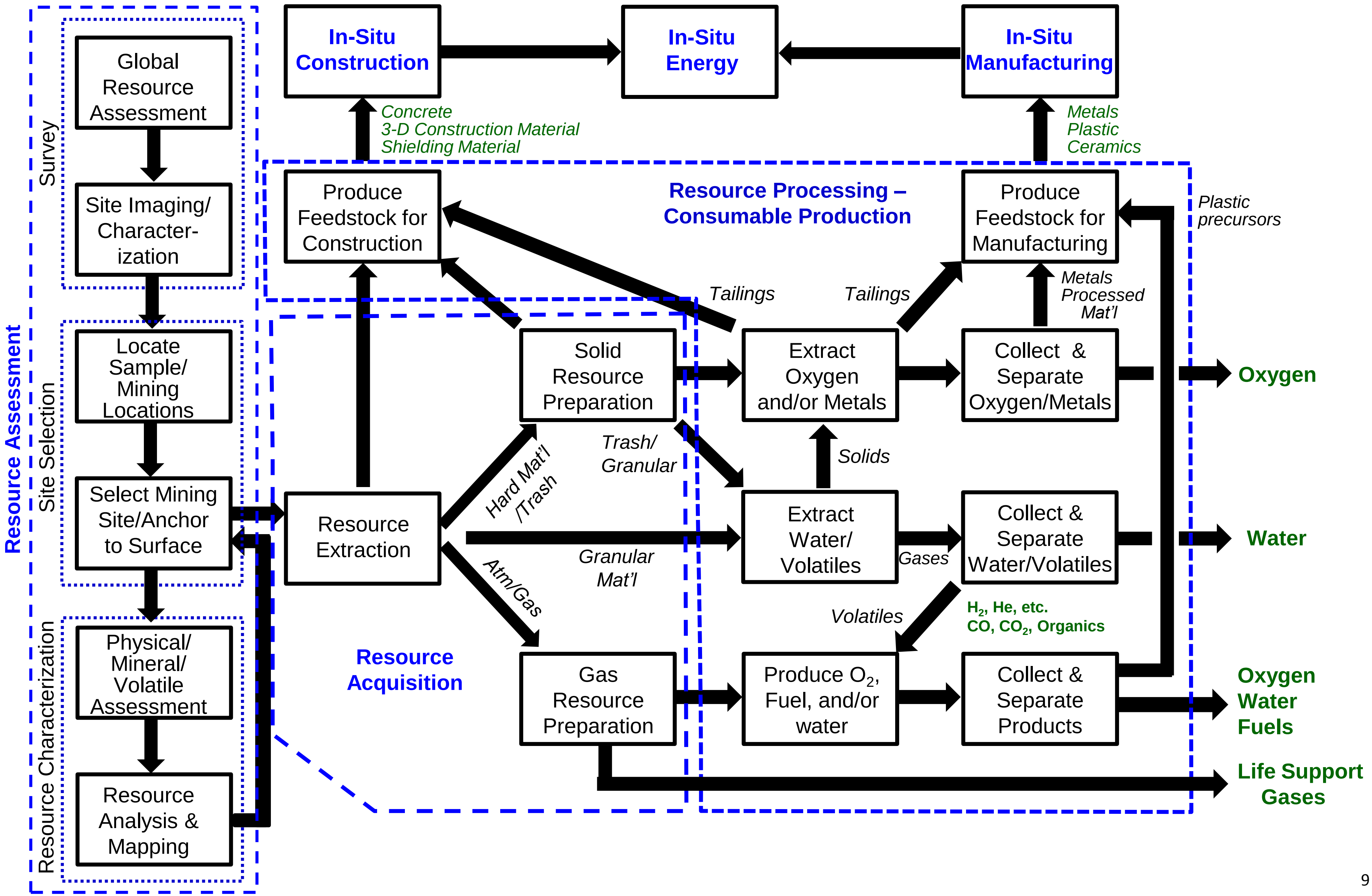
- A key piece to the Pioneering Space strategy is input from System Maturation Teams (SMTs). The SMTs are made up of subject matter experts involved in maturing systems and advancing technology readiness for NASA.
- SMTs allow NASA to shift from mission-driven development to a more flexible, capability-driven development.
- SMTs are responsible for defining
  - Performance parameters, metrics, and goals
  - Assessing the State-of-the-art in capabilities
  - Identifying performance and capability gaps
  - Developing maturation plans and roadmaps for flexible pathways to Mars
  - Specify, the interfaces between the various capabilities
  - Prioritize the importance of ISRU capabilities in support of the EMC
  - Define Proving Ground satisfaction criteria and future Flight Test Objectives
  - Ensure that the capabilities mature and integrate to enable future pioneering missions.

ISRU Capabilities – Functions - Discriminators

Capabilities	Functions	Sub-Functions	Discriminators	Performance Characteristics
Resource Assessment	Site Imaging/Characterization	Surface Imaging/Characterization Subsurface Imaging/Characterization	Destination, Resource Feedstock, Gravity, Resource Depth & Profiling, Level of Autonomy Operating Requirement	Sample Size, Depth of Sample, Accuracy, Volatiles Identified, Elements/Minerals Identified
	Physical Property Evaluation	Imaging; Direct contact Direct contact (cone pen.; shear vane, etc.)		
	Atmosphere/Gas Resource Evaluation	Physical Property Measurements Gas Constituent Measurements (element, molecule, isotopic) Dust/Particulate Physical Measurements Dust/Particulate Chemical Measurements		
	Mineral/Chemical Resource Evaluation	Sample Preparation Spectroscopy (active/passive)		
	Volatile Resource Evaluation	Surface/Subsurface Sample Acquisition Sample Heating Volatile Analysis		
	Data Integration, Analysis, & Mapping			
Resource Acquisition (Collection, Transfer, & Preparation)	Atmosphere/Gas Resources	Dust Particle Filtration Gas Constituent Separation & Capture (CO_2, N_2, Ar) Gas Resource Preparation (compression, recycling)	Destination, Resource Feedstock, Resource Concentration, Gravity, Resource Depth & Profiling, Feedstock Preparation Level of Autonomy Energy Type Requirement Operating Requirement	Extraction Rate, Operation Duration, Effective Mass, Effective Power Operating Cycles
	Planetary Material Resources	Regolith (granular) Excavation & Transfer Hydrated Soil Excavation & Transfer Icy-Soil Excavation & Transfer Rocky Material Excavation & Transfer Crushing Sizing Sorting Mineral Beneficiation		
	Discarded Material/Trash Resources	Shredding Separation Transport		
Consumable Production - Resource Processing	Extract/Produce Oxygen	1, 2, 3, 4, 5, 6, 7, 8	Destination, Resource Material, Resource Concentration, Mission Criticality, Gravity Level of Autonomy Processing Approach Operating Requirement	Production Rate, Batch Size, Extraction-Conversion Efficiency, Operation Duration, Effective Mass, Effective Power Effective Volume Operating Cycles
	Extract/Produce Fuel	1, 2, 3, 4, 5, 6, 7, 8		
	Extract/Produce Water	1, 5, 6, 7, 8		
	Extract/Separate Gases for Life support/Science	1, 4, 7, 8		
	Extract/Produce Manufacturing Feedstock	1, 2, 3, 4, 5, 6, 7		
	Extract/Produce Construction Feedstock	1, 2, 3		
	Extract/Produce Food Production Feedstock	1, 2, 3, 4, 5, 6, 7		
In-Situ Construction - Civil Engineering	Area Clearing, Landing Pads, Roads	Clearing; Leveling Surface Hardening; Concrete	Destination, Resource Material, Consumble Feedstock, Mission Criticality, Gravity Level of Autonomy Operating Requirement	Production Rate, Operation Duration, Effective Mass, Effective Power
	Excavation - Berms, Trenches, Burial			
	Structure/Habitat Construction	Molds 3-D Additive manufacturing		
	Shielding Construction			

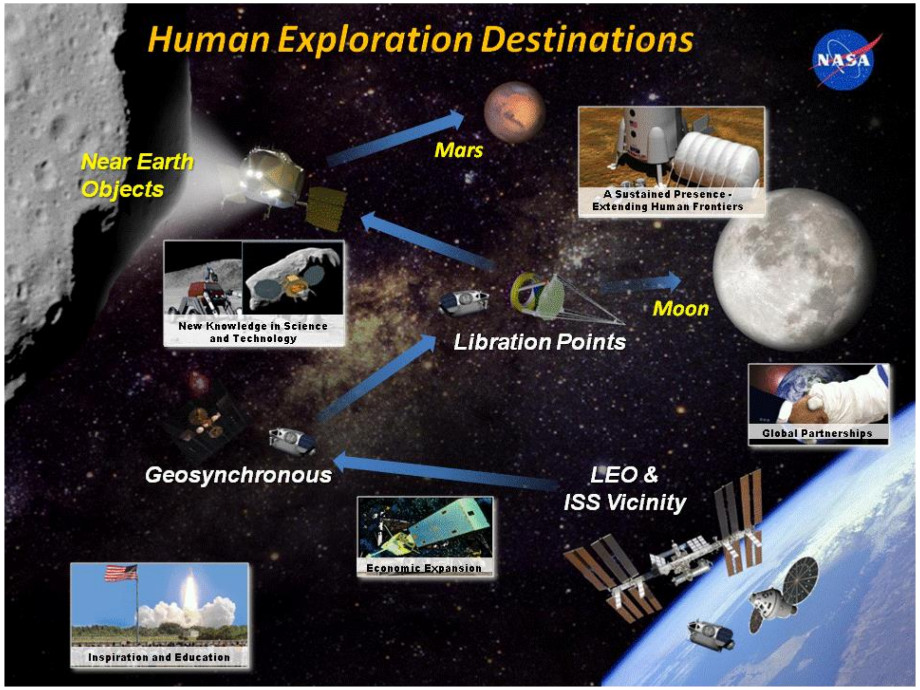
1. Gas/Solid Processing Reactors
2. Liquid/Solid Processing Reactors
3. Gas/Liquid or Molten Processing Reactors
4. Gas/Gas Processing Reactors
5. Biological Processing Reactors
6. Water Processing
7. Product-Reactant Separation
8. Contaminant Removal

ISRU Capability-Function Flow Chart



Multiple Pathways to Mars

Each pathway identifies similar ISRU capabilities



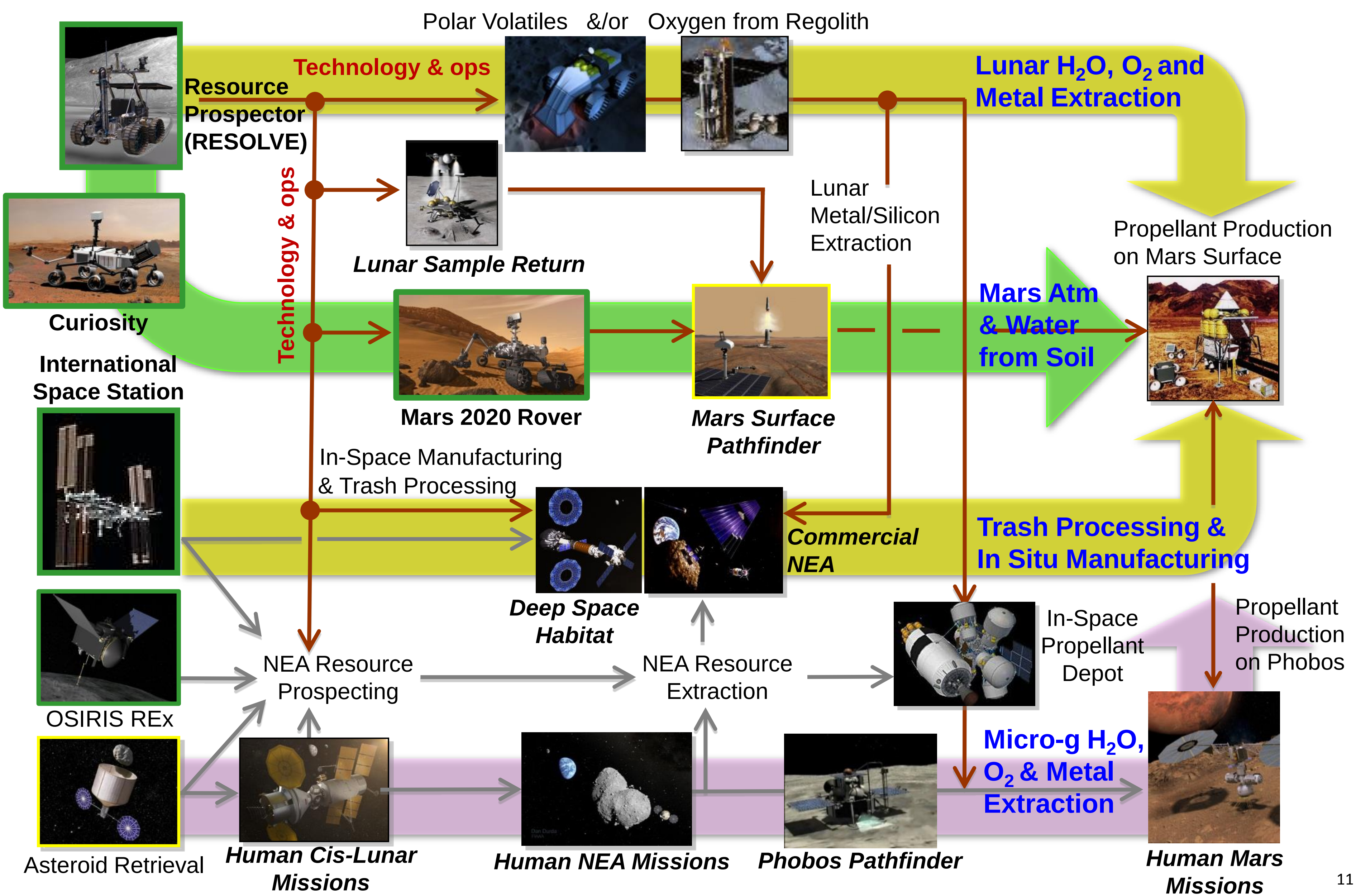
Moon Pathway

- **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

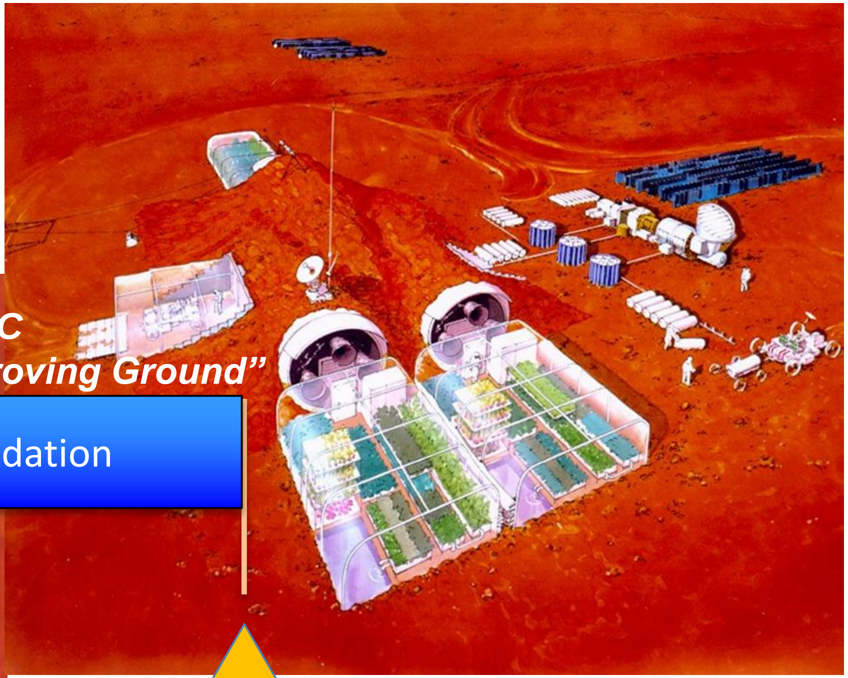
Cis-Lunar/NEA/Phobos Pathway

- **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

Notional ISRU Mission Evolution
– Primary Pathways and Priorities



Architecture Approach within the EMC – Mars Surface



Emplacement

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

1

EMC
"Mars Surface Proving Ground"

Consolidation

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

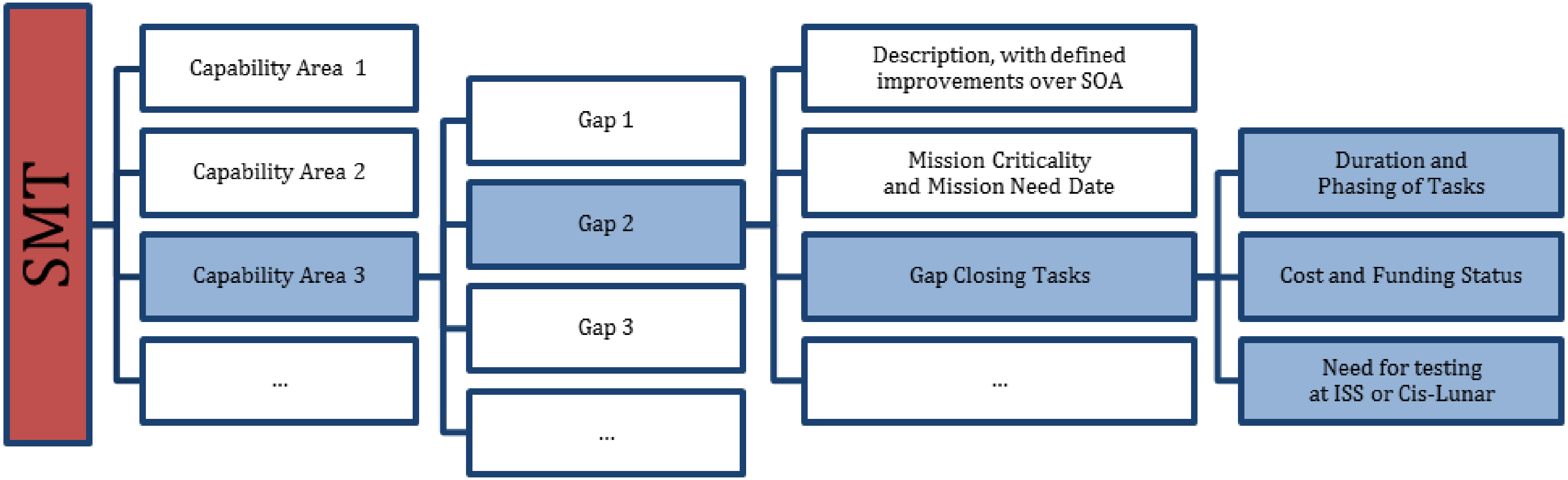
Utilization

- **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):

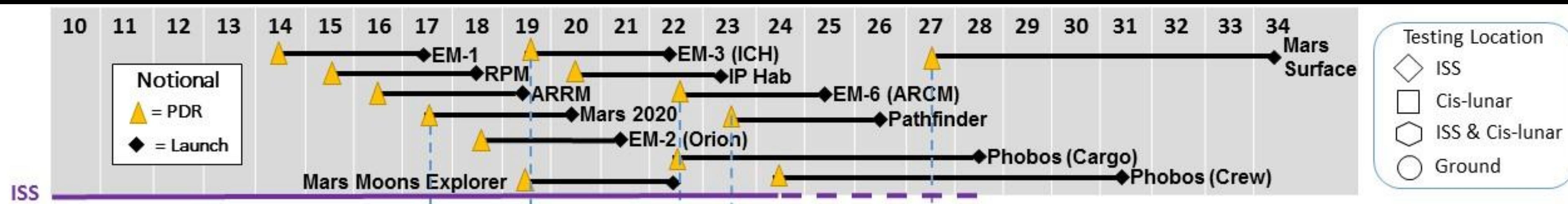
ISRU SMT								EMC Performance Parameters
Cap	Funct	Discrim	Gap	Where needed?	Performance			
					Threshold	Desired	SOA	
Resource Assessment	Characterization and Evaluation	Accuracy	Locate lunar polar water/volatile resources	Resource Prospector (RP)	5 day mission; 1 m depth; 2 to 4 3-cm samples per site; 2 sites over 1 km; Volatiles: 70 amu; 50% accuracy of H_2O content	2 solar periods; 4 6-cm samples per site, >4 sites over 3 km; Volatiles <20% accuracy of H2O content	RESOLVE breadboard hardware; Flight XRF, Mossbauer, microscopes, and other instruments	RPM: Resource processing – 0.02 yrs lifetime. RPM listed as a pathfinder mission in EMC for Mars water resource extraction and not for lunar exploration Mars water resource prospecting under discussion in EMC wrt site selection; Performance requirements in work with MEPAG for orbital and surface accuracy **Needs to be coordinated with SKG Measurement SMT, Mars Landing Site Selection, and SMD-MEPAG**
			Locate Mars water resources	Mars Pathfinder EDL, Mars surface		>30 sols; 1 m depth; 4 6-cm samples per site, >15 sites over 3 km; Volatiles: 150 amu, <20% accuracy of H2O content	DAN and SAM instruments on MSL (72 samples, 150 amu); RESOLVE and RP. Mars drill technology	
			Locate NEA/Phobos resources (water, volatiles, metals) and identify physical characteristics.	ARRM, Mars Moons Explorers, ARCM, Phobos		3 m depth; >5 sites; 8 samples (>100 gms) per site; 150 amu, <20% accuracy of H2O content	Impactors and instruments used on Rosetta, Hayabusa II, Dawn, and OSIRIS-REX	Initial capability descriptions for NEA prospecting of captured asteroid in trans-lunar space provided to EMC in 2014 by HAT Task 11A Asteroid ISRU team. **Similar capabilities should be utilized for Phobos Pathfinder. Coordinate with SKG Measurement**

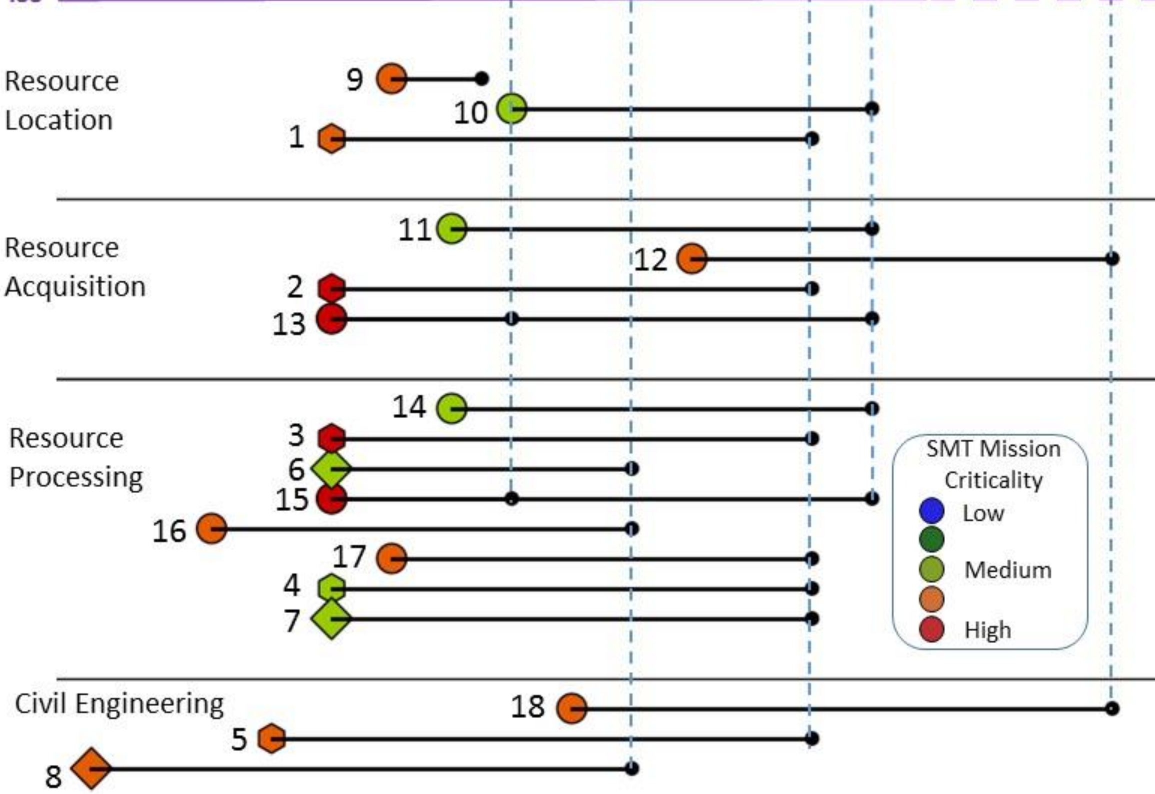
SMT Work Product Structure

- SMT work product structure
  - Capability area
  - Performance gap
  - Performance gap closing tasks
    - Description and parameters



ISRU Capability Development for *Notional* EMC Missions





Gaps have to be tested on ISS and in Cis-lunar	
1. Locate NEA/Phobos resources [ARCM]	2. NEA/Phobos Regolith Acquisition [ARCM]
3. NEA/Phobos soil processing for volatiles [ARCM]	4. Regolith processing for O_2 [ARCM]
5. Construction of Structures [ARCM]	
Gaps have to be tested on ISS	
6. Crew trash/waste processing [ICH]	7. Regolith processing for metals [ARCM]
8. In Situ manufacturing [ICH]	
Gaps tested on the Ground	
9. Locate Lunar polar water/volatile resources [RPM]	10. Locate Mars water resources [Pathfinder]
11. Lunar/Mars Regolith/Hydrated Soils Acquisition [Pathfinder]	12. Mars polar/icy Regolith Acquisition [Mars Surface]
13. Mars Atmosphere CO_2 Acquisition [Pathfinder]	14. Moon/Mars Soil Processing for Water/Volatile Extraction [Pathfinder]
15. CO_2 Processing into O_2 [Pathfinder]	16. CO_2 Processing into O_2/Fuel [ICH]
17. Water Processing [ARCM]	18. Civil Engineering [Mars Surface]

Each task is further broken down into subtasks

First need date [mission] specified in brackets

ISRU Gap Closing Assessment & Plans

SMT	Gap	Description	Duration & Cost (years & ROM)	Start Dev./ Testing in Next 5 Years?	SMT Criticality	Rationale for Criticality Score (SMT)	Gap closing task	Description	Duration (Years)	Cost (ROM) $M	Funding Status Funded/Partial Funded/Not Funded	Need ISS?	Need Cis-Lunar?
ISRU													
23	Resource Location												
ISRU	Locate lunar polar water/volatile resources	Involves characterization and mapping of physical, mineral, chemical, volatile, and water resources.	4 yrs/$20M	Yes	4	Understanding the availability of water/volatiles on the Moon can significantly influence lunar and EMC mission architecture decisions						No	No
							Task #1	Complete RESOLVE instrument/oven/sample acquisition development	1.5		Funded - RP/RESOLVE		
							Task #2	Upgrade RESOLVE for longer duration mission/operations in shadowed region	3		Not Funded		
							Task #3	Add instruments for physical/soil mechanics for shadowed region	2.5		Not Funded		
							Task #4	Add instruments for mineral characterization for shadowed region	2.5		Not Funded		
ISRU	Locate Mars water resources	Involves characterization and mapping of physical, mineral, chemical, volatile, and water resources.	6 yrs/$22M	No	3	Use of water resources is currently not baselined but could significantly increase mission performance						No	No
							Task #1	Develop sample acquisition subsystem and/or coring subsystem	3		Some funding in SMD ROSES		
							Task #2	Modify SAM and/or RESOLVE GC/MS for multiple operations and larger samples	3		Not Funded		
							Task #3	Develop and evaluate both downhole, captured material on auger, and dedicated reactor for water extraction	3		SBIR selected		
							Task #4	Downselect acquistion, processing, and measurement options for integration and testing	3		Not Funded		
ISRU	Locate NEA/Phobos resources (water, volatiles, metals) and identify physical characteristics.	Involves characterization and mapping of physical, mineral, chemical, volatile, and water resources.	8 yrs/$26M	Yes	4	Not understanding the resources available on the captured asteroid significantly reduces the rationale for ARM						No	Yes
							Task #1	Perform basic research on micro-g material handling, transfer and processing (Phase I/II approach)	3		SBIR and ESI funding		
							Task #2	Develop down hole and material transfer and reactor heating concepts	3		SBIR and ESI funding		
							Task #3	Develop volatile capture and measurement capabilities based on missions: RP, Curiosity, ROSETTA	3		Not Funded		
							Task #4	Downselect acquistion, processing, and measurement options for integration and testing	4				
24	Resource Acquisition												

Findings & Recommendations from ISRU SMT

Findings

- It is important that during proving ground missions are aimed at understanding and using resources in space (Moon, Mars, asteroids, Phobos) leading to the goal of Earth independence.
- While ISRU production of oxygen for human Mars ascent has been baselined, Mars soil processing for water extraction will significantly enhance and enable Earth Independence
- lunar oxygen production (75 to 80% of chemical propulsion mass) and lunar volatile/ice extraction may be architecture driving capabilities for cis-lunar and Mars exploration.
- The stabilization and elimination of crew trash/waste in space and on the Mars surface is a volume and logistic burden, and a planetary protection issue that could be turned into a benefit through processing into gases and propellant
- the advent of additive manufacturing and significant logistics mass and delivery delays associated with human Mars missions, in space manufacturing with eventual feedstock from in situ resources is required for Earth Independence

Recommendations

- In the next 5 years, work should focus on gaps in capabilities associated with
  - Resource prospecting (Moon-Resource Prosperctor, Mars, NEA),
  - Mars oxygen production
  - Mars oxygen/fuel production
  - Lunar/Mars soil excavation and processing for water
  - Trash processing into gas or propellants.
- To minimize cost and risk, closer development and integration with ECLSS (including trash management), power, and propulsion is highly recommended.

Questions ?