Human Mission Architectures and Approaches and Concepts for Incorporating In Situ Resource Utilization (ISRU)

Graduate Seminar Series – SSERVI CLASS

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Why and How to Incorporate ISRU into Human Exploration

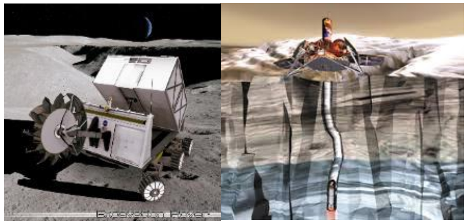
What is *In Situ* Resource Utilization (ISRU)?

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)

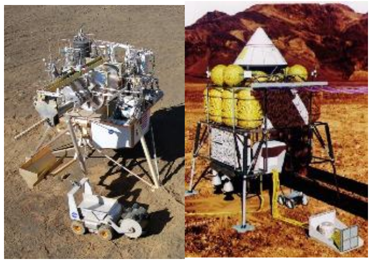
Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition



Extraction, excavation, transfer, and preparation/ beneficiation before Processing

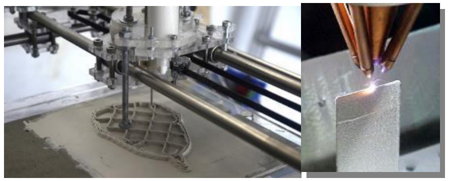
Resource Processing/ Consumable Production



Processing resources into products with immediate use or as feedstock for construction & manufacturing

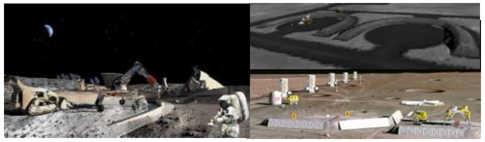
- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



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

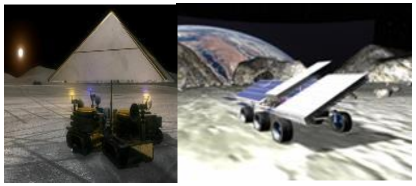
In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from in situ resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy

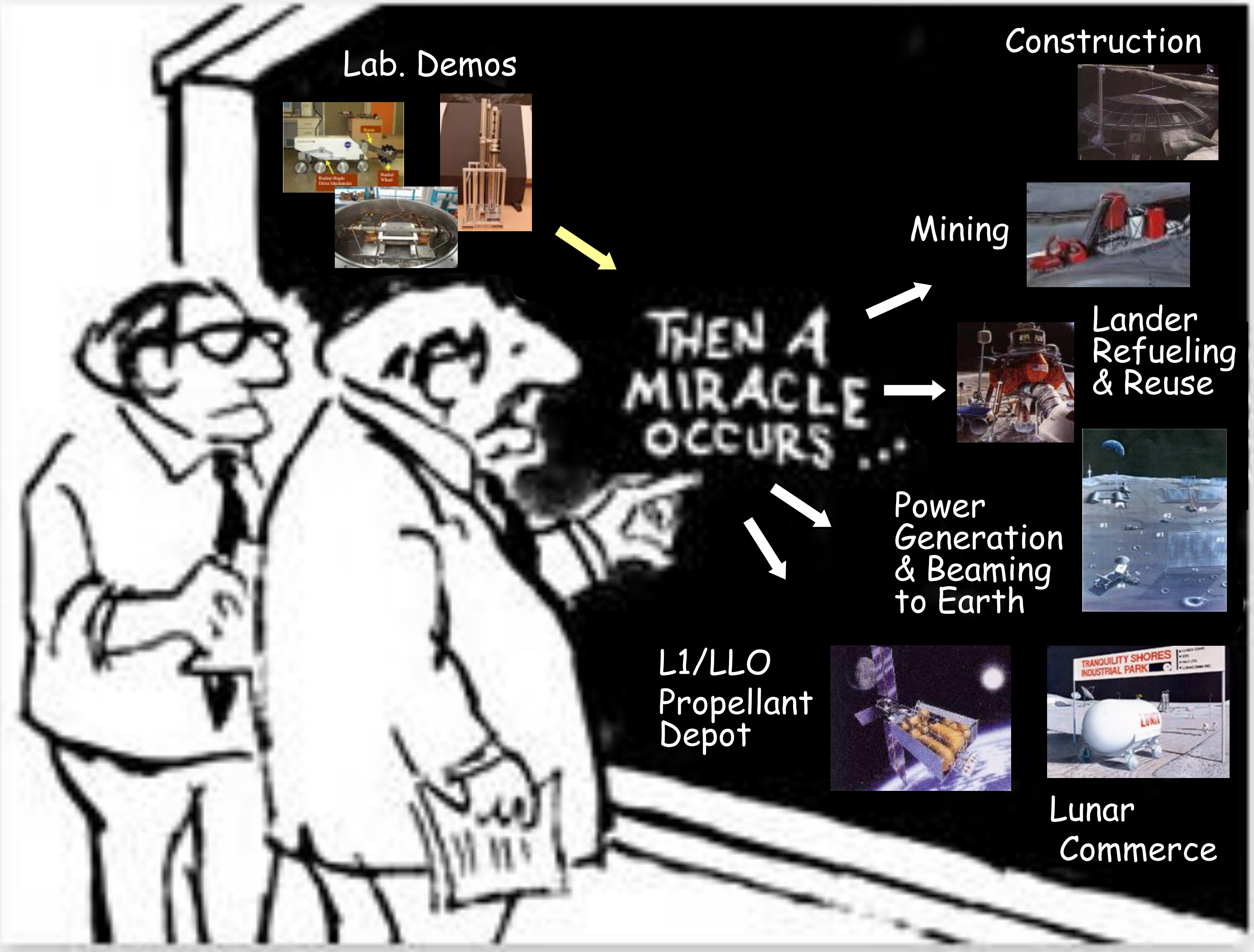


Generation and storage of electrical, thermal, and chemical energy with in situ derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

- **'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 users/customers of ISRU products and services

Early ISRU Development & Implementation Roadmap



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

Two Approaches to Inserting ISRU into Human Exploration Architectures

- **Evolve Sustainability** - ISRU When Its Ready
  - No reusable transportation elements at the start of the architecture
  - ISRU & propellant depots not in initial critical path to mission success
  - Demonstrate ISRU capabilities early
  - Design Architecture to incorporate ISRU products and services when adequately demonstrated
  - On ramp for Space Commercialization of products

Low Risk but High Life Cycle Costs

- **Sustainability as Driver** - ISRU From Start
  - Develop transportation and power elements with ISRU consumables and reusability in mind.
  - Propellant depots and ISRU in critical path; Use Earth-based propellants until ISRU capabilities up and running
  - human and cargo landers synergistic with Moon & Mars
  - Utilize Earth supplied propellants for depot until ISRU is fully demonstrated
  - Consider Space Commercialization of products from the start

Higher Upfront Costs but more Sustainable

Main Points for Incorporation of ISRU into Human Mission Plans

- **ISRU should be viewed as a 'solution' to enable Affordable, Safe, and Sustainable Human Exploration**
  - Increase sustainability/decrease life cycle costs
  - Increase mission performance and capabilities
  - Reduce mission and crew risks
  - Increase Science
  - Support exploration of multiple destinations

- **ISRU Strategy for Human Exploration**
  - Define areas of ISRU and impact on human exploration
  - Understand phasing/implementation approach
  - Understand challenges and gaps to implementation

Do not manage missions based on scarcity/limitations; instead exploit abundances provided by in situ resources

Potential ‘Solutions’ Provided by Incorporation of ISRU

Increase Sustainability/Decreases Life Cycle Costs

- Reduce launch mass and/or number of launchers required
- Reuse landers and transportation elements can provide significant cost savings
- Growth in capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Increase Mission Performance and Capabilities

- 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

Reduce Mission and Crew Risks

- Minimizes/eliminates life support consumable delivery from Earth
- Increases crew radiation protection over Earth delivered options
- Can relax critical requirements in other system performance
- Minimizes/eliminates ascent propellant boiloff leakage issues
- Minimizes/eliminates landing plume debris damage

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

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

Pros & Cons of Human Exploration with ISRU

Pros	Cons
Enables Reusability & Flexibility	Higher initial risk
Increased delivered payloads/reduced consumables from Earth	Higher upfront costs
Interdependence – common hardware, interfaces, and standards	Interdependence - common failure modes across multiple subsystems
Long-term growth/reduced life cycle costs	Does not benefit short trips/stays
Linked objectives w/ Science; increased Science rationale and capabilities	Concern about impacting lunar environment and Mars search for life for science
Supports Commercial involvement/reduced costs	International agreement/Legal issues
Multi-Destination	Lunar/Mars must consider from start
Public Outreach & Interest. Not repeating Apollo	
Technology Spin-In and Spin-off	

ISRU Influence on Mission Architectures

ISRU has greatest influence at the site of the resource/production

- **Transportation (propellant is the largest 'payload' mass from Earth)**
  - Crew ascent from Moon/Mars surface
    - O_2 only provides up to 80% of propellant mass
    - O_2/fuel – full asset reuse and surface hopping
  - Crew/Cargo ascent and descent from Moon/Mars surface – reusable
  - Supply orbital depots for in-space transportation
    - Cis-lunar (L1 to GEO or LEO)
    - Trans-Mars

- **Power (mission capabilities are defined by available power)**
  - Nighttime power storage/generation
    - Fuel cell reactants – increase amount and regeneration
    - Thermal storage
  - Mobile power – fuel cell reactants
  - Power generation: in situ solar arrays, 'geo'thermal energy

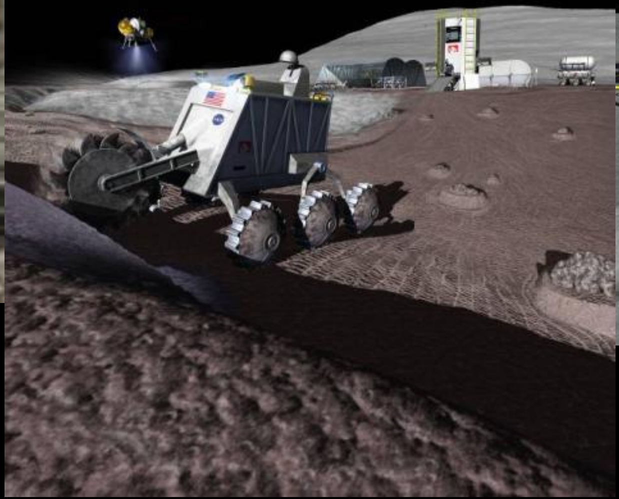
- **Infrastructure and Growth**
  - Landing pads and roads to minimize wear and damage
  - Structures and habitats

- **Crew Safety**
  - Radiation protection
  - Logistics shortfalls (life support consumables, spare parts)

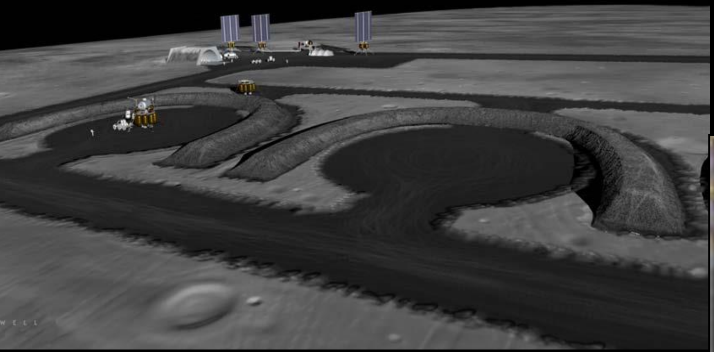
Lunar ISRU Mission Capability Concepts

Resource Prospecting – Looking for Polar Ice

Excavation & Regolith Processing for O_2 Production

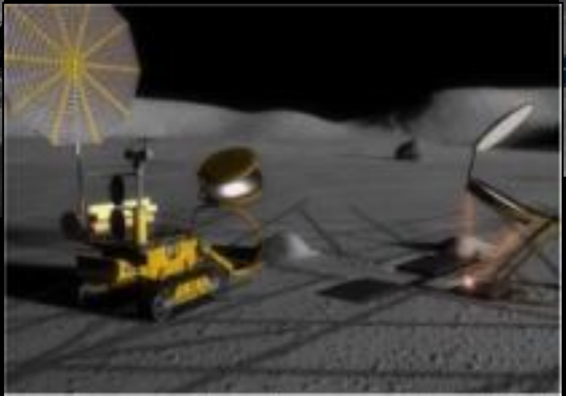


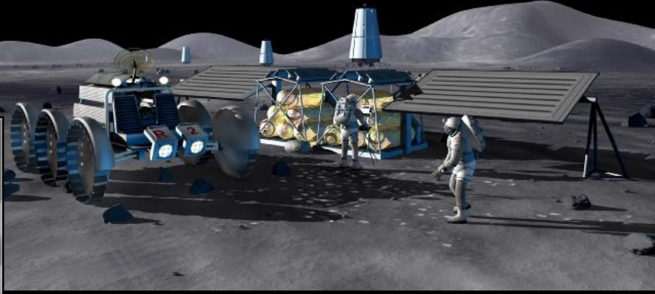
Carbothermal Processing with Altair Lander Assets



Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





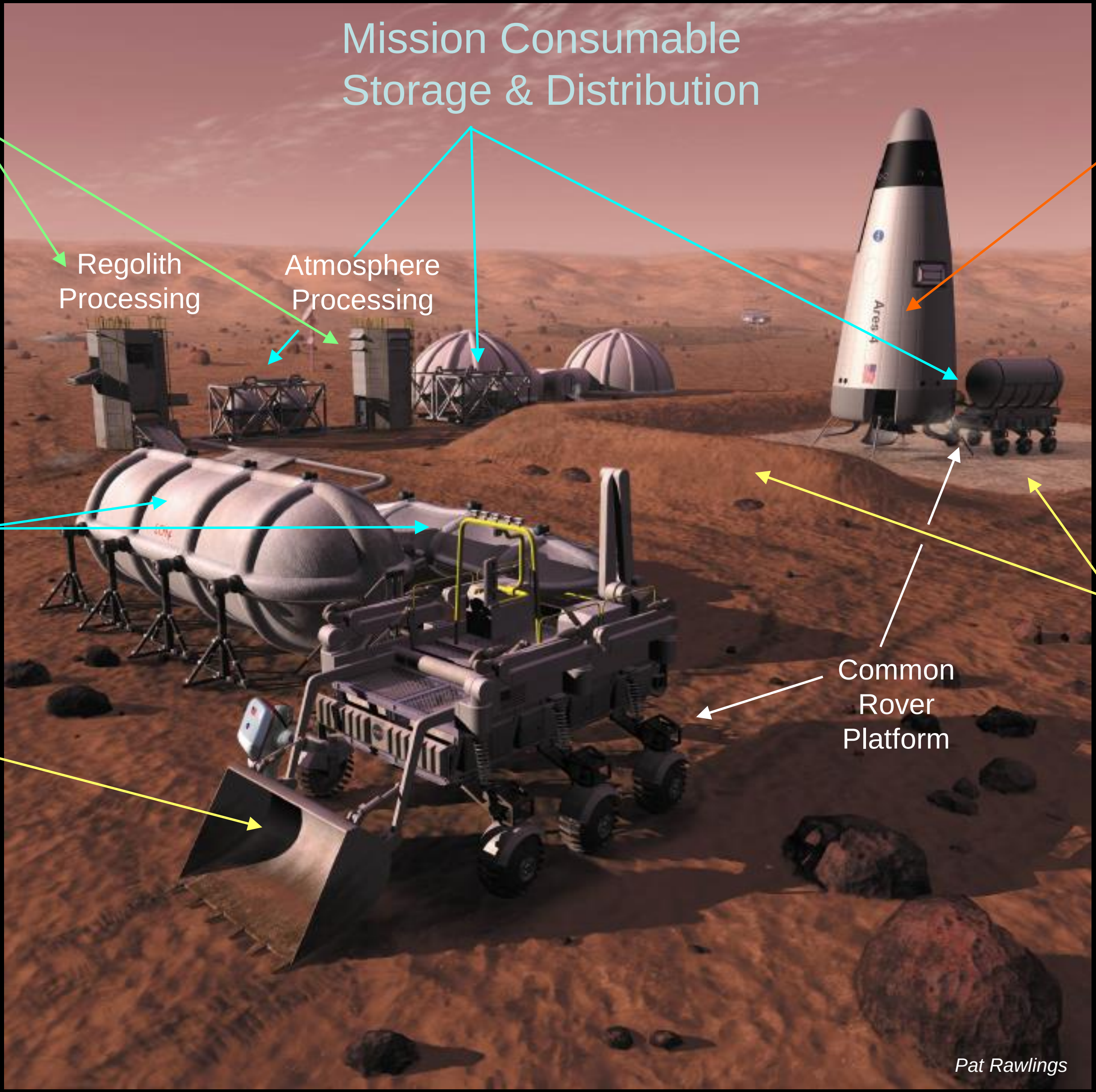
Consumable Depots for Crew & Power

Mars ISRU Mission Capability Concepts

Resource Processing/ Plants

Collapsible/ Inflatable Cryogenic Tanks

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



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

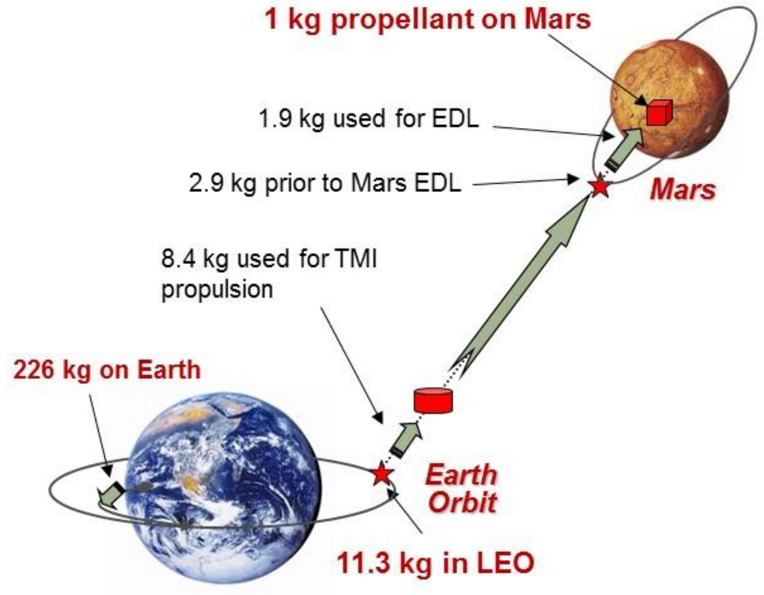
Landing pad & plume exhaust berm

Leverage (Gear) ratios using ISRU

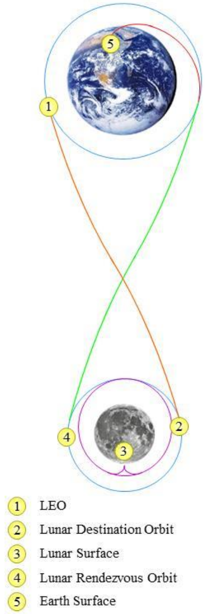
Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

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



Estimates based on Aerocapture at Mars



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

Evaluating Impact of ISRU on Transportation Architectures

Three Parts to Analyzing the Impact of ISRU on Transportation Systems

- ISRU Propellants: What are the propellants that can be made and what form/where are the propellants used/delivered?
- ISRU Infrastructure: What is the mass, power, volume of ISRU plant and infrastructure (power, storage tanks, etc.) to make the propellants?
- Cost of ISRU: What is considered when determining the cost of ISRU vs Non-ISRU architectures? Only ISRU unique development or all infrastructure required? Are launch costs considered?

Architecture Design Drivers on ISRU Benefits

- Number of missions and how often: *greater number shortens return on investment*
- Pre-deployment vs All-in-one mission: *longer production times/reduces infrastructure mass*
- Rendezvous/Depot Orbits: *increase in Delta-V increases benefit of ISRU propellants*
- Reusability: *reuse allows for single stage landers, allows for Hub-and-Spoke surface exploration, and lowers cost for orbital propellant depots*
- Abort Strategy- to surface or orbit: *abort to surface enables surface depot use*
- Other uses for ISRU products*: supporting radiation shielding, life support, manufacturing, and construction increases production need and return on investment*

ISRU Design Drivers on ISRU Benefits

- Resource type and concentration: regolith or volatile resource
- Resource extraction process: Energy and time required to extract the resource of interest
- Resource Location: Ease of access to resource: depth, terrain, mineral/hardness, powder or rock
- Processing Location: amount of sunlight, communications with Earth, environment, Delta-V to site

Economics of ISRU

Whether a resource is 'Useful' is a function of its *Location* and how *Economical* it is to extract and use

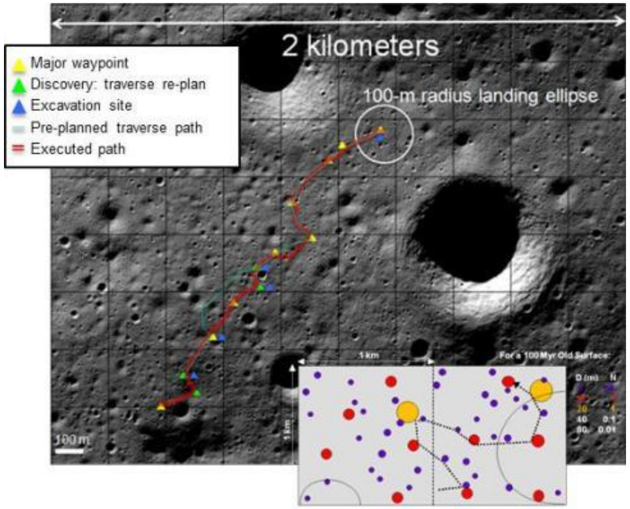
- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
  - Resource must be within reasonable distance of transportation and delivery of product to 'market': habitats, landers, orbital depots, etc.

- **Resource extraction must be 'Economical'**
  - **Concentration and distribution of resource and infrastructure needed to extract and process the resource must allow for Return on Investment (ROI)** for:
    - Mass ROI - mass of equipment and unique infrastructure compared to brining product and support equipment from Earth
    - Cost ROI - cost of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - Time ROI - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
    - Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth: launch mass limits, time gap between need and delivery, etc.
  - **Amount of product needed must justify investment in extraction and processing**
    - Requires long-term view of exploration and commercialization strategy to maximize benefits
    - Metric: mass/year product vs mass of Infrastructure
  - **Transportation of product to 'Market' (location of use) must be considered**
    - Use of product at extraction location most economical

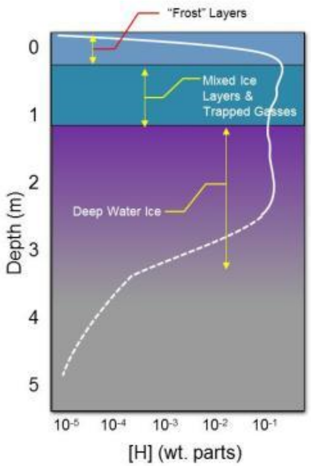
Economic Assessment of ISRU

Need to assess the extent of the resource ‘ore body’

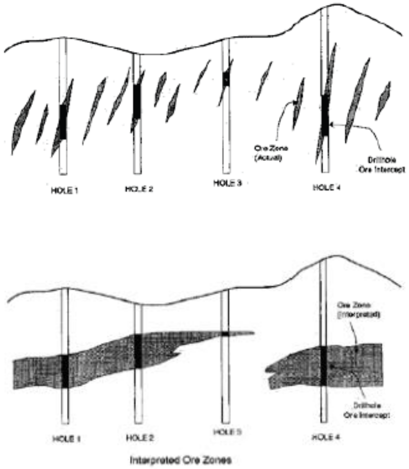
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



An ‘Useful’ Resource Depends on What is needed, How much is needed, How often it is needed, and How difficult is it to extract the resource

Potential Lunar Resource Product Needs

- 1,000 kg oxygen (O_2) per year for life support backup (crew of 4)
- 3,000 kg of O_2 per lunar ascent module launch from surface to L_1/L_2*
- 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L_1/L_2 (fuel from Earth)*
- 30,000 kg of O_2/Hydrogen (H_2) per reusable lunar lander to L_1/L_2 (no Earth fuel needed)*

***Note: ISRU production numbers are only 1st order estimates for 4000 kg payload to/from lunar surface**

Potential Mars Resource Product Needs

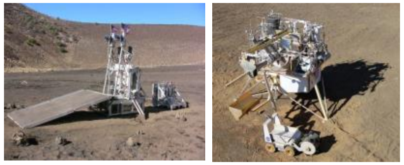
- 20,000 to 25,000 kg of oxygen (O_2) per ascent mission
- 5700 to 7150 kg of methane (CH_4) per ascent mission
- 14,200 kg of water (H_2O) per ascent mission

ISRU Examples and Analogies

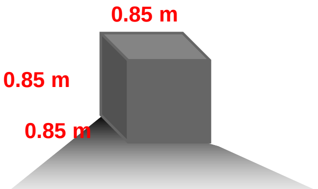
- Excavation rates required for lunar 10 MT O_2/yr production range based on extraction efficiency of process selected and location
  - H_2 reduction at poles (~1% efficiency): 150 kg/hr
  - CH_4 reduction (~14% efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr
- Excavation rates required for 14.2 MT H_2O/mission production range based on water content
  - Hydrated soil (3%): 41 kg/hr
  - Icy soil (30%): 4 kg/hr

- Cratos & LMA rovers: 10 to 20 kg/bucket in <5 min.at field test in Hawaii

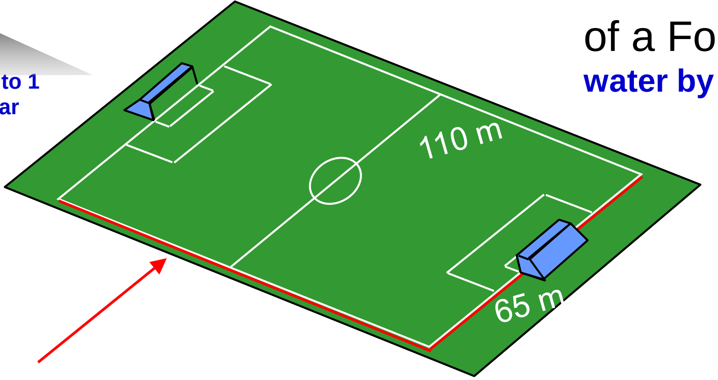
- Robotic Mining Challenges:
  - 2009: 437 kg in 30 min.; remote operation
  - 2015: 118 kg in 20 min; autonomous operation



- Soil Processing
  - ROxygen: 5-10 kg/hr
  - PILOT: 4.5-6 kg/hr
  - Pioneer SBIR: 4 kg/hr
  - MISME: 0.2 kg/hr

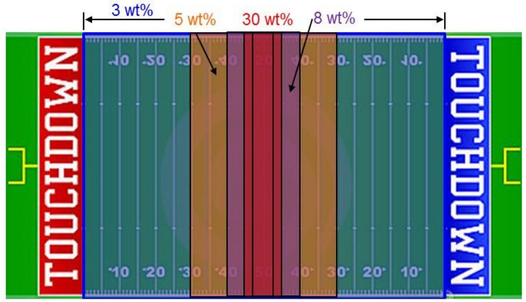


Volume equivalent to 1 Metric Ton of lunar regolith



10 MT of lunar oxygen per year requires excavation of a Soccer field to a depth of **0.6 to 8 cm!** **(14% to 1% efficiencies)**

14.2 MT of Mars water per mission requires excavation of a Football field to a depth of 1.1 to 9.6 cm! **(30% to 3% water by mass)**



H_2O 1.238 kg/hr Soil 1500 kg/m3
480 days Ice 940 kg/m3

Water wt%	Soil wt%	Water kg	Soil kg	Total kg	Extraction 80%	Ave Density kg/m3	Tot Vol m3	FB Depth cm	FB Field yds
3	97	14261.76	461130.2	475392.0	594240.0	1483.20	400.65	9.58	100.00
5	95	14261.76	270973.4	285235.2	356544.0	1472.00	242.22	5.79	60.46
8	92	14261.76	164010.2	178272.0	222840.0	1455.20	153.13	3.66	38.22
30	70	14261.76	33277.4	47539.2	59424.0	1332.00	44.61	1.07	11.14
70	30	14261.76	6112.2	20373.9	25467.4	1108.00	22.99	0.55	5.74

Evaluation Criteria for ISRU Insertion

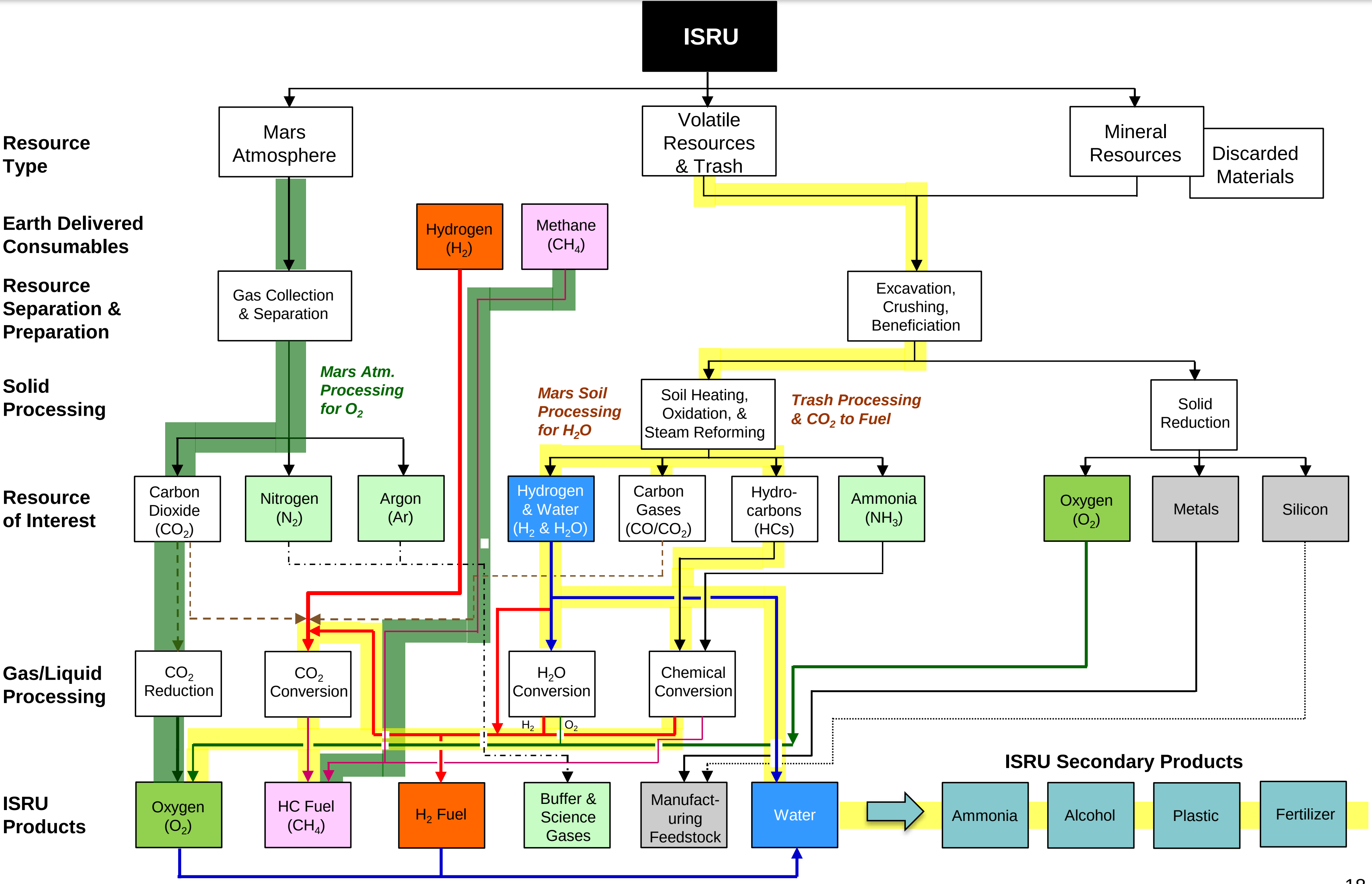
When Evaluating ISRU Concepts, you need to evaluate the following:

- ‘Launch mass saved’ or ‘Additional mass to surface’
- Process and operation complexity
- Process scalability
- Ability to operate without human presence
- System power, mass & volume
- Mass of product/service vs Mass of ISRU “system”
- Amount of infrastructure and ease of delivery/deployment required before products are delivered for use
- Logistical support needs
  - Reactant/reagent losses and replacement brought from Earth
  - Hardware replacement. Reliability - Mean-time between failure

It’s not about being able to do ISRU.
It’s not about having the most efficient ISRU system.

It is about achieving the benefits of ISRU
for a reasonable cost, mass, and risk.

ISRU Consumables Production Decision Tree



ISRU

Resource Type

Mars Atmosphere

Volatile Resources & Trash

Mineral Resources

Discarded Materials

Earth Delivered Consumables

Hydrogen (H_2)

Methane (CH_4)

Resource Separation & Preparation

Gas Collection & Separation

Excavation, Crushing, Beneficiation

Solid Processing

Mars Atm. Processing for O_2

Mars Soil Processing for H_2O

Soil Heating, Oxidation, & Steam Reforming

Trash Processing & CO_2 to Fuel

Solid Reduction

Resource of Interest

Carbon Dioxide (CO_2)

Nitrogen (N_2)

Argon (Ar)

Hydrogen & Water (H_2 & H_2O)

Carbon Gases (CO/CO_2)

Hydrocarbons (HCs)

Ammonia (NH_3)

Oxygen (O_2)

Metals

Silicon

Gas/Liquid Processing

CO_2 Reduction

CO_2 Conversion

H_2O Conversion

H_2

O_2

Chemical Conversion

ISRU Products

Oxygen (O_2)

HC Fuel (CH_4)

H_2 Fuel

Buffer & Science Gases

Manufacturing Feedstock

Water

ISRU Secondary Products

Ammonia

Alcohol

Plastic

Fertilizer

Lunar Resources and Propellant Options

Propellant Options

Extracted **Processed**

Four major resources on the Moon:

REGOLITH

Ilmenite - 15%

$FeO \cdot TiO_2$	98.5%

Pyroxene - 50%

$CaO \cdot SiO_2$	36.7%
$MgO \cdot SiO_2$	29.2%
$FeO \cdot SiO_2$	17.6%
$Al_2O_3 \cdot SiO_2$	9.6%
$TiO_2 \cdot SiO_2$	6.9%

Olivine - 15%

$2MgO \cdot SiO_2$	56.6%
$2FeO \cdot SiO_2$	42.7%

Anorthite - 20%

$CaO \cdot Al_2O_3 \cdot SiO_2$	97.7%

SOLAR WIND VOLATILES (Apollo Data)

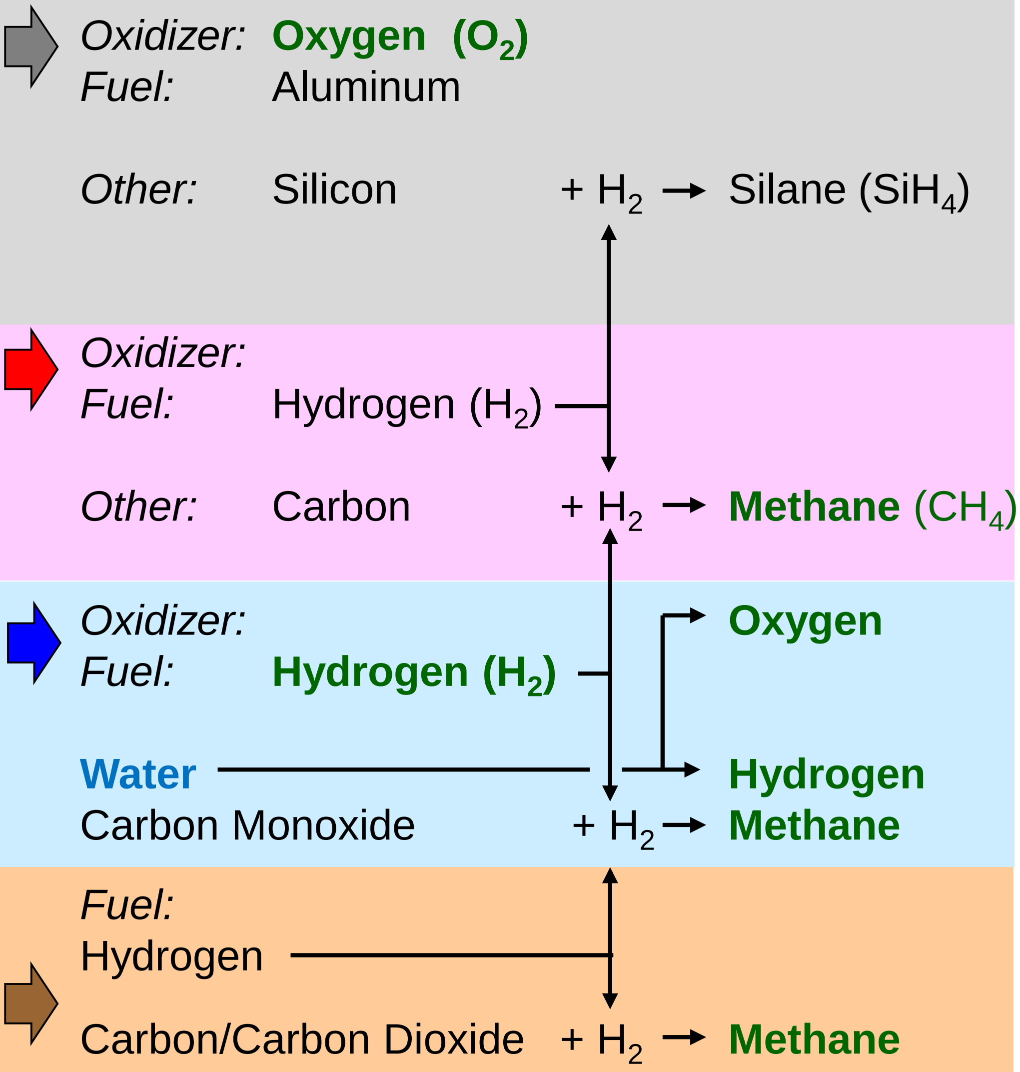
Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm

POLAR/NEA VOLATILES

Carbon Monoxide (CO)	5.7%
Hydrogen (H_2)	1.4%
Water/Ice (H2O)	5.5%
M³ OH/H_2O	0.1 to 0.8% on surface
LAMP H_2O Frost	1 to 2% on surface
Mini SAR	Potential ice sheets

TRASH/WASTE

Plastic/packaging
Food/Plant/Bio Waste
Carbon Structures



Oxidizer: **Oxygen (O_2)**
Fuel: Aluminum

Other: Silicon + H_2 → Silane (SiH_4)

Oxidizer:
Fuel: Hydrogen (H_2)

Other: Carbon + H_2 → **Methane** (CH_4)

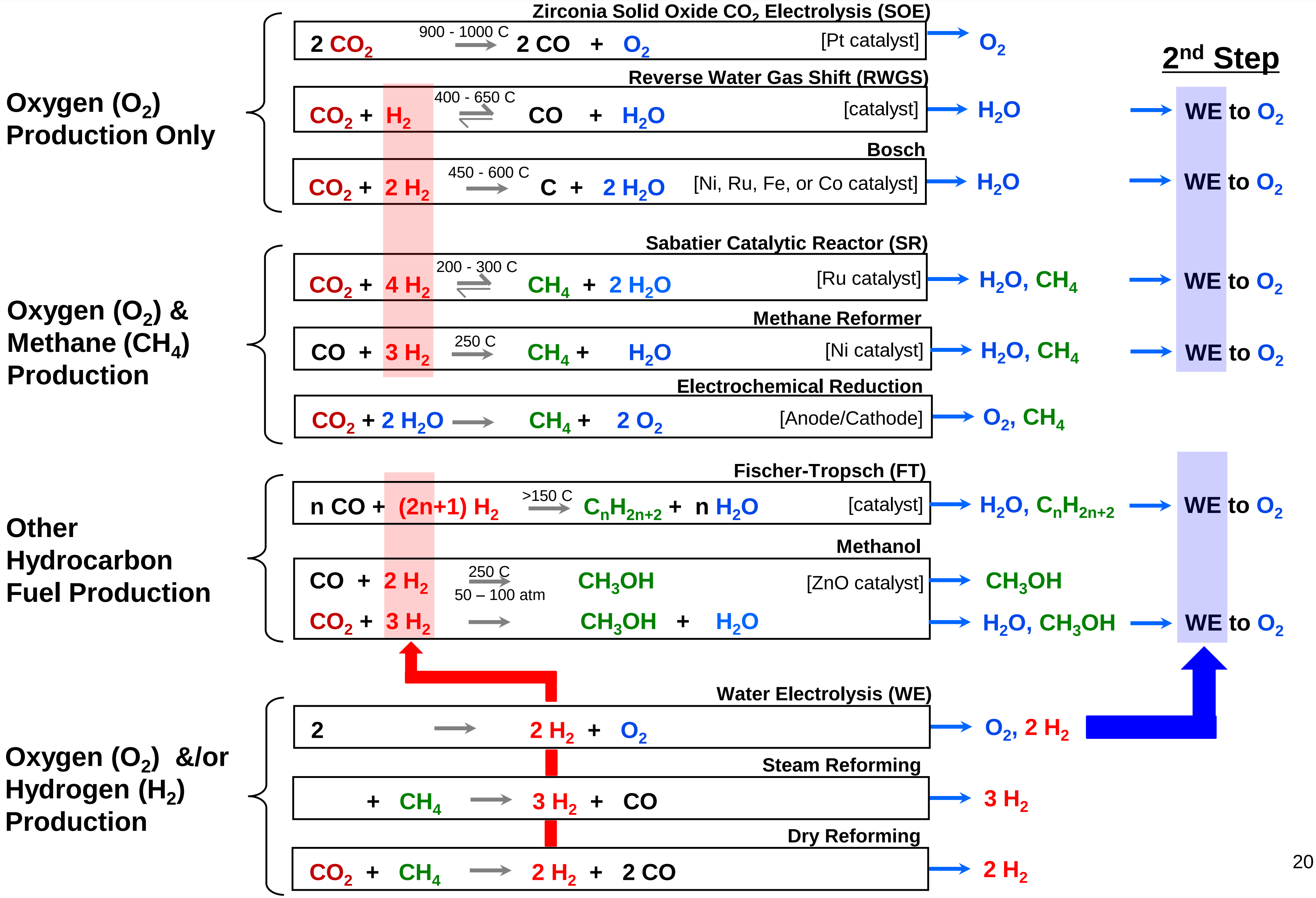
Oxidizer: **Oxygen**
Fuel: **Hydrogen (H_2)**

Water → **Hydrogen**
Carbon Monoxide + H_2 → **Methane**

Fuel:
Hydrogen

Carbon/Carbon Dioxide + H_2 → **Methane**

The Chemistry of Mars ISRU



2nd Step

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)

$2\ CO_2 \xrightarrow{900 - 1000\ C} 2\ CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)

$CO_2 + H_2 \overset{400 - 650\ C}{\rightleftharpoons} CO + H_2O$ [catalyst] → H_2O → **WE to O_2**

Bosch

$CO_2 + 2\ H_2 \xrightarrow{450 - 600\ C} C + 2\ H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → **WE to O_2**

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)

$CO_2 + 4\ H_2 \overset{200 - 300\ C}{\rightleftharpoons} CH_4 + 2\ H_2O$ [Ru catalyst] → H_2O, CH_4 → **WE to O_2**

Methane Reformer

$CO + 3\ H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → **WE to O_2**

Electrochemical Reduction

$CO_2 + 2\ H_2O \rightarrow CH_4 + 2\ O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)

$n\ CO + (2n+1)\ H_2 \xrightarrow{>150\ C} C_nH_{2n+2} + n\ H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → **WE to O_2**

Methanol

$CO + 2\ H_2 \xrightarrow[50 – 100\ atm]{250\ C} CH_3OH$ [ZnO catalyst] → CH_3OH

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → **WE to O_2**

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)

$2 \quad \rightarrow 2\ H_2 + O_2$ → $O_2, 2\ H_2$

Steam Reforming

$+ CH_4 \rightarrow 3\ H_2 + CO$ → $3\ H_2$

Dry Reforming

$CO_2 + CH_4 \rightarrow 2\ H_2 + 2\ CO$ → $2\ H_2$

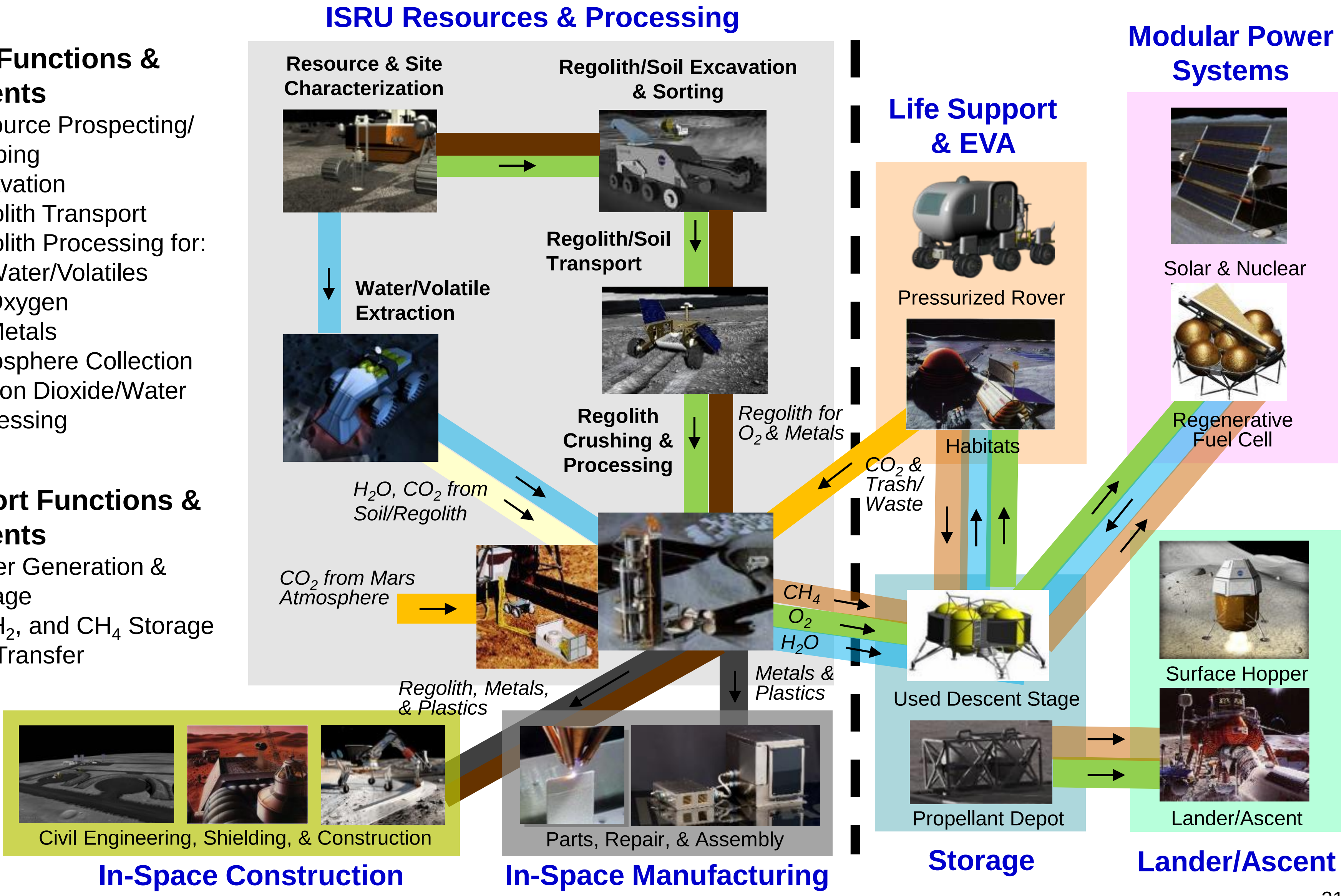
ISRU Integrated with Exploration Elements
(Mission Consumables)

ISRU Functions & Elements

- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing

Support Functions & Elements

- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer



ISRU Resources & Processing

Resource & Site Characterization

Regolith/Soil Excavation & Sorting

Regolith/Soil Transport

Water/Volatile Extraction

Regolith Crushing & Processing

Regolith for O_2 & Metals

H_2O, CO_2 from Soil/Regolith

CO_2 from Mars Atmosphere

CO_2 & Trash/ Waste

CH_4

O_2

H_2O

Regolith, Metals, & Plastics

Metals & Plastics

Life Support & EVA

Pressurized Rover

Habitats

Modular Power Systems

Solar & Nuclear

Regenerative Fuel Cell

Used Descent Stage

Propellant Depot

Storage

Surface Hopper

Lander/Ascent

Lander/Ascent

Civil Engineering, Shielding, & Construction

In-Space Construction

Parts, Repair, & Assembly

In-Space Manufacturing

ISRU Development and Implementation Challenges

Space Resource Challenges

- What resources exist at the site of exploration that can be used?
  - Are there enough of the right resources; Return on Investment
- What are the uncertainties associated with these resources?
  - Form, amount, distribution, impurities/contaminants
- How to address planetary protection requirements?

ISRU Technical Challenges

- Is it technically feasible to collect, extract, and process the resource?
- How to maximize performance/minimize mass
- How to achieve high reliability and minimal maintenance requirements?
- How to minimize power through thermal management integration and taking advantage of environmental conditions?

ISRU Operation Challenges

- How to operate in extreme environments, including temperature, pressure, dust, and radiation?
- How to achieve long duration, autonomous operation and failure recovery?
- How to operate in low gravity or micro-gravity environments?
  - Anchoring/weight-on-bit
  - Friction, cohesion, and electrostatic forces may dominate in micro-g

ISRU Integration Challenges

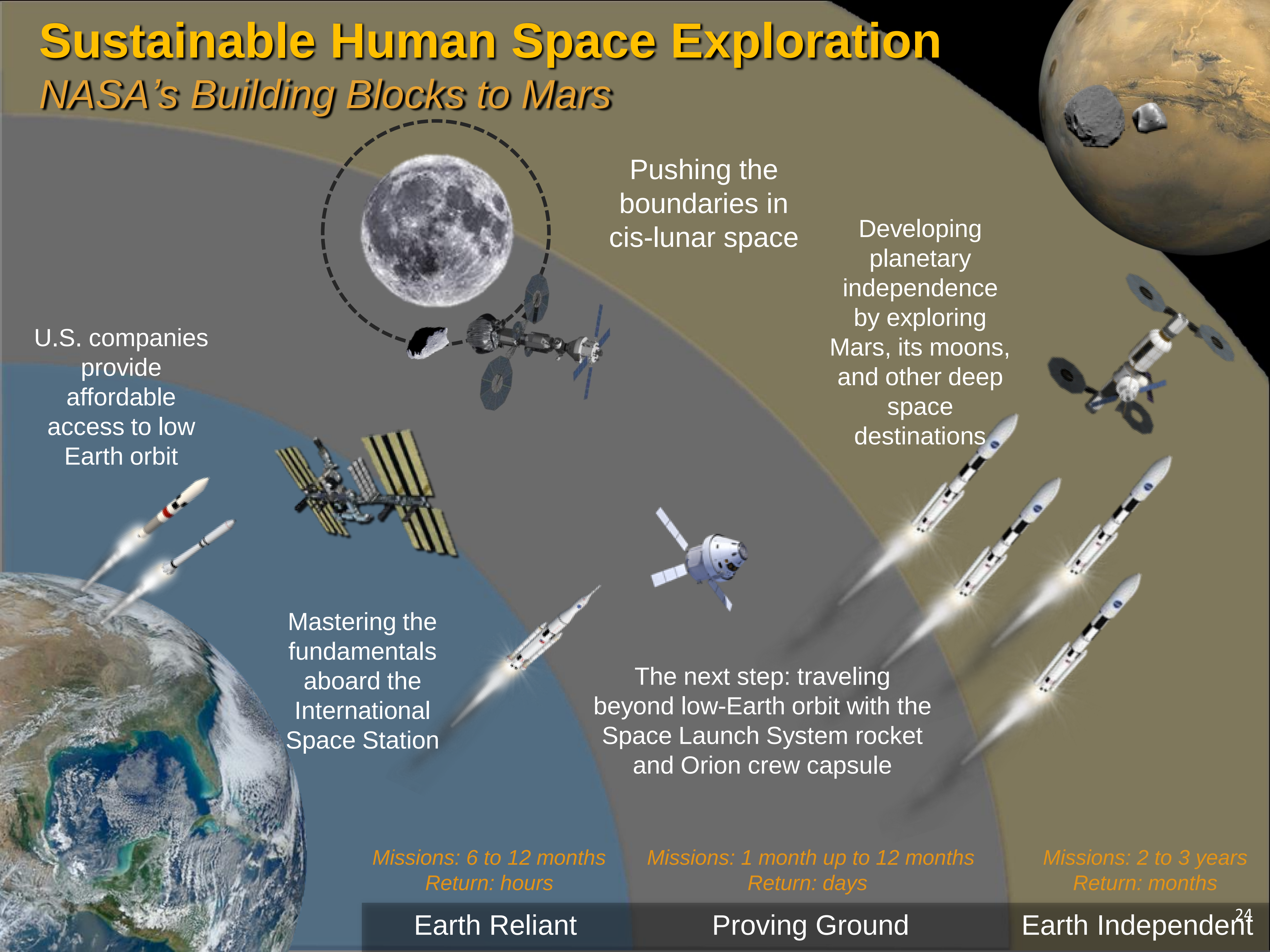
- How to optimize at the architectural level rather than the system level?
- How are other systems designed to incorporate ISRU products?
- How to manage the physical interfaces and interactions between ISRU and other systems?
- How to establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Overcoming these challenges requires a multi-discipline and integrated approach

Evolvable Mars Campaign & ISRU

Sustainable Human Space Exploration

NASA's Building Blocks to Mars



U.S. companies provide affordable access to low Earth orbit

Mastering the fundamentals aboard the International Space Station

Pushing the boundaries in cis-lunar space

The next step: traveling beyond low-Earth orbit with the Space Launch System rocket and Orion crew capsule

Developing planetary independence by exploring Mars, its moons, and other deep space destinations

Missions: 6 to 12 months
Return: hours

Earth Reliant

Missions: 1 month up to 12 months
Return: days

Proving Ground

Missions: 2 to 3 years
Return: months

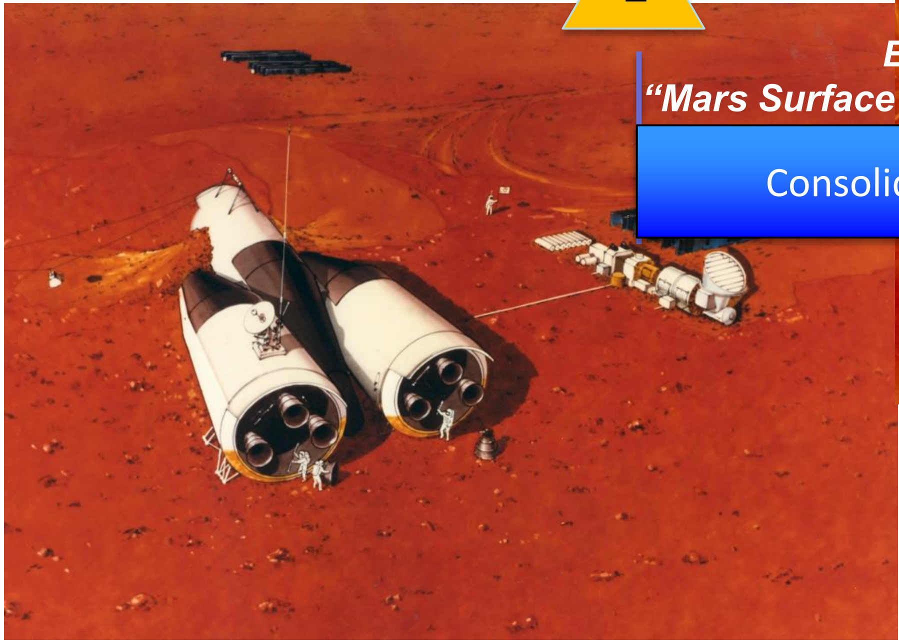
Earth Independent

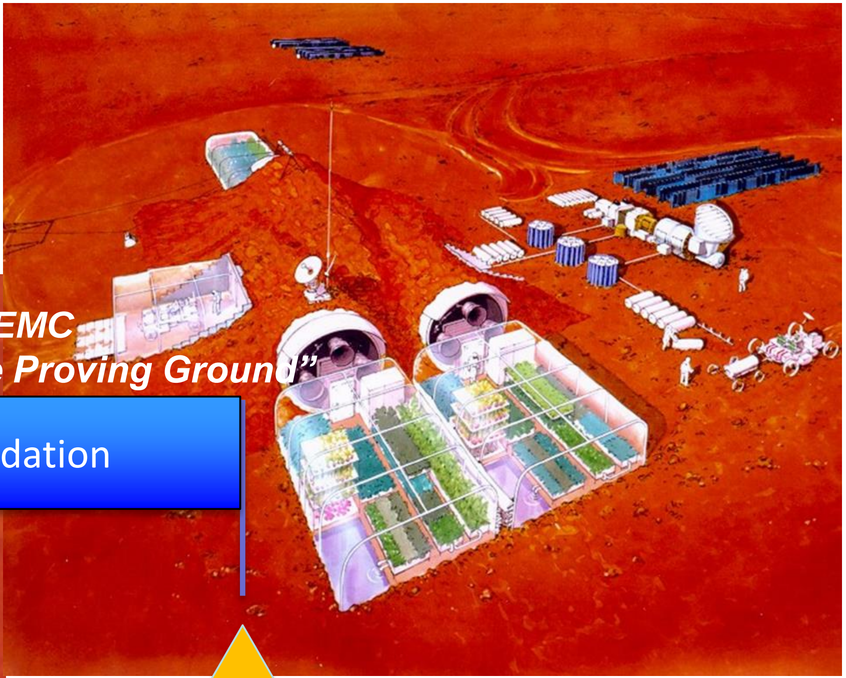
Architecture Approach within the EMC – Mars Surface

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

Primary Objectives and Defining Characteristics by Phase

- Emplacement - Establish a human presence on the surface of Mars.
  a) Development of an interplanetary transportation system, EDL, and basic habitation needs for human crews
  b) Establishment of surface equipment and science instruments
  c) Laying the foundation for future, more complex surface operations
    - Clearing human crews (i.e., physiological and psychological suitability) and basic infrastructure (i.e., habitation and power systems) to operate on the surface for 12 - 18 continuous months without resupply. Human crews explore at ranges of tens of kilometers away from the surface facilities; robotic systems explore tens to hundreds of kilometers away.

- Consolidation - Learn to become independent of Earth.
  a) Developing a deeper understanding of the Mars environment and how to live/work within the constraints it imposes
  b) Developing and testing alternative combinations of systems and operations that will break reliance on Earth in those areas not already achieved during the Emplacement phase, including expanded reliance on local resources
  c) Improving confidence in overall operational strategies; day-to-day activities are conducted without continual supervision and guidance from support staff on Earth. Human and robotic operations are routinely conducted at ranges of hundreds of kilometers from the outpost.

- Utilization - Demonstrate basic Earth independence with crews of up to four people (TBR) cleared to remain indefinitely at the surface outpost with minimal (ideally zero) resupply.
  a) Routine use of and reliance on in situ resources (broad definition) to support and sustain the crew and operations
  b) Maintaining a continuous presence on the surface but with crew rotation. The area of exploration opportunities is expanded to include routine human access to more distant points on the planet (many hundreds to thousands of kilometers).

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: Site-dependent Resources

- **Sequence of knowledge/analyses needed**
  - Global understanding of resources/terrain to select landing sites
  - Higher resolution data for regions of interest (ROI) for landing
  - 1 meter or less resolution of terrain and <100 m resolution of resources in locations within ROI for landing site selection and preliminary infrastructure layout plans
  - <5 m resolution of resources to select mining sites of interest
  - <1 m mapping of terrain, surface/subsurface features and resources with ground truth verification of resources (and contaminants) at statistically relevant intervals to plan and perform mining operations and finalize mining hardware designs

Orbital/ Aerial

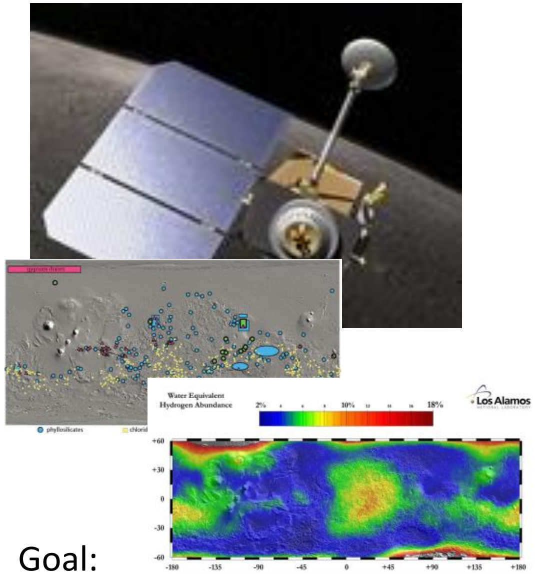
Aerial/ Surface

- **Different ISRU phasing strategies can influence scope and timing of resource assessment**
  - Strategy 1: Start with lowest risk resource (hydrated mineral at surface) near initial infrastructure before or during 1st crewed mission. Perform resource evaluation and ISRU risk reduction demos on larger quantity/higher concentration resources as time goes on with crew present
  - Strategy 2: Identify the resource type of primary interest. Locate and perform ISRU risk reduction demos on that resource before crew arrives

Mars Resource Assessment

Remote Assessment

Orbiters



Goal:

i. Obtain data on terrain, minerals, and water resources to select landing sites of consideration

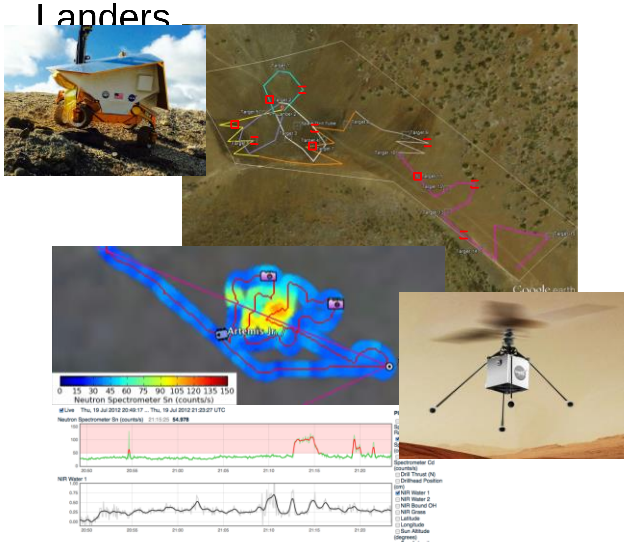
ii. Obtain data at resolution to plan surface Exploratory Assessment of terrain and resources

Instruments

- Better mineral resolution for chemistry and hydration
- Passive and active subsurface hydrogen and layer

Exploratory Assessment

Options: Rovers, Hoppers, Aerial Vehicles, Impactors, Instrumented Landers



Goals:

i. Obtain data on physical/mineral characteristics and water/volatiles.

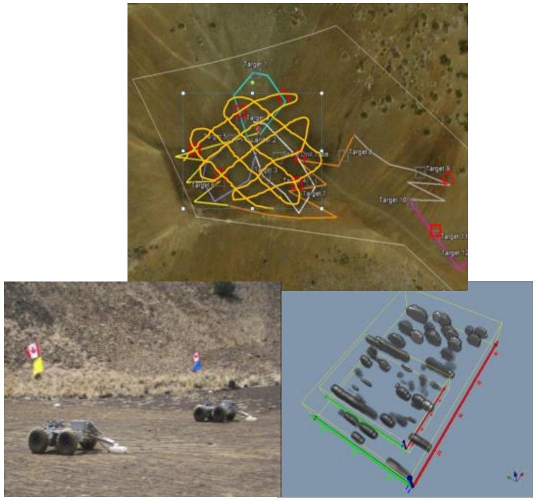
ii. Obtain sufficient data to determine if the site warrants a Focused Assessment of resources

Instruments

- Should cover physical/geotech, chemical/mineral, and volatile characterization
- Passive and active subsurface assess

Focused Assessment, Mapping, & Planning

Rover or Crew



Goals:

i. Ensure sufficient resources exist in form and location expected

ii. Build 3-D interpretation of data to define resource for mining operations

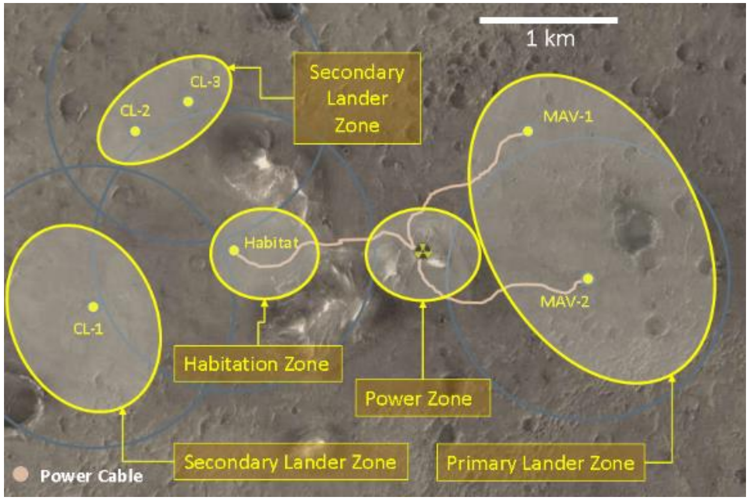
Instruments

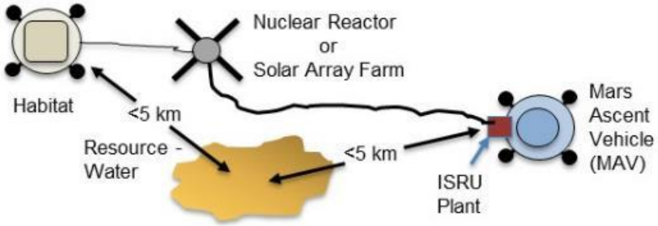
- Should cover physical, chemical/mineral, and volatile characterization
- Passive and active subsurface assess

ISRU Products, Operations, and Resources Grow As Mission Needs and Infrastructure Grow

Initial Conditions:

- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

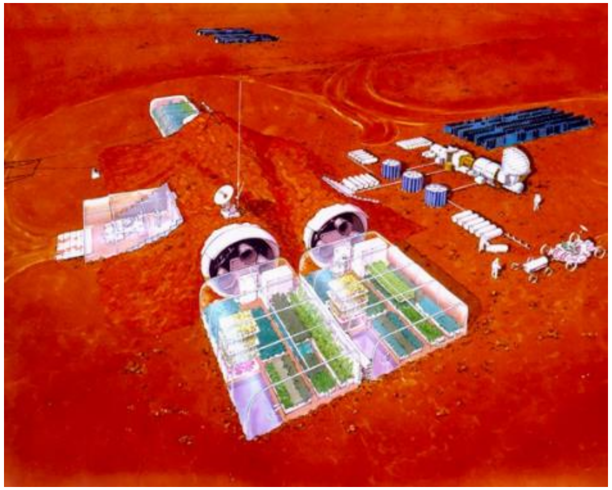


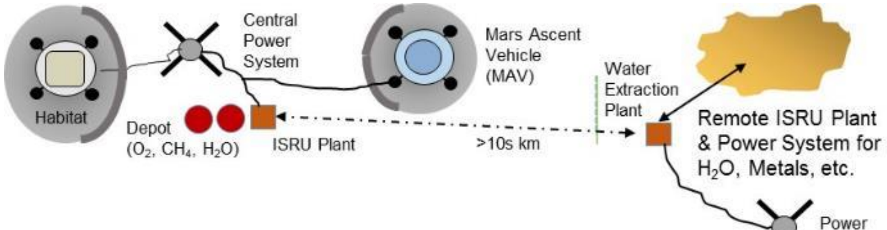


- **ISRU hardware integrated with Landers**
- **Resource very close to landing site/Ascent vehicle**

Ultimate Goal

- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independent; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.

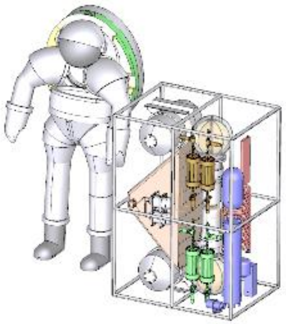




- **ISRU Plants consolidated with Product Storage**
- **Civil Engineering and In Situ Construction operations**
- **Resources can be farther from Habitat and Ascent Vehicle**

Mars ISRU: Atmosphere & Water Resource Attributes

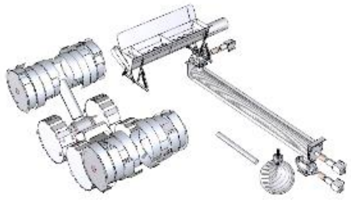
Atmosphere Processing

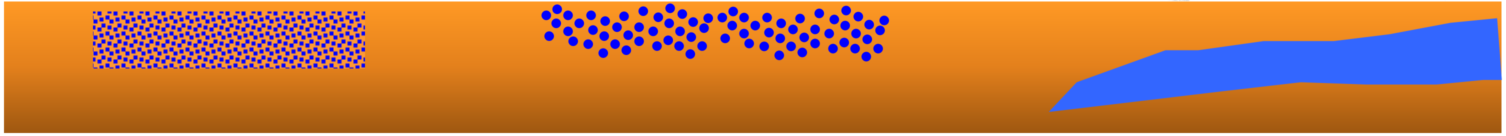


Atmosphere

- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Atm. temperature: +35 C to -125 C
- **Everywhere on Mars;** Lower altitude the better
- Chemical processing similar to life support and regenerative power

Granular Regolith Processing for Water





Mars Garden Variety Soil

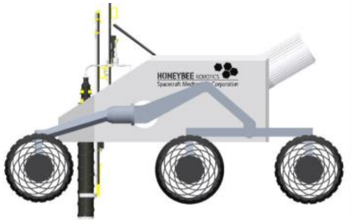
- **Low water concentration 1-3%**
- **At surface**
- **Granular; Easy to excavate**
- **300 to 400 C heating for water removal**
- Excavate and transfer to centralized soil processing plant
- **Most places on Mars**; 0 to +50 Deg. latitude

Gypsum/Sulfate Processing for Water

Gypsum or Sulfates

- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

Icy Regolith Processing for Water



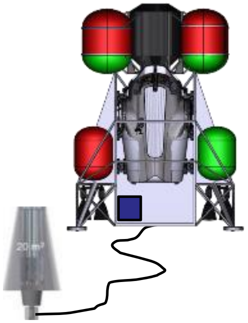
Subsurface Ice

- **90%+ concentration**
- **Subsurface glacier or crater**: 1 to 3 m from surface possible
- Hard material
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater;** >40 to +55 Deg. latitude

Increasing Complexity, Difficulty, and Site Specificity

ISRU Consumable “Rich” Architecture

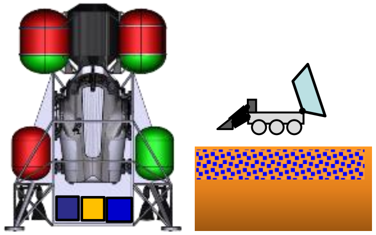
Ascent O_2 Production



ISRU Processes
- Atm. CO_2 to O_2

ISRU Products
- 20 to 24 mT O_2

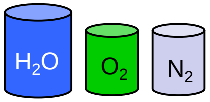
Ascent O_2 & CH_4 Production



ISRU Processes
- Atm. Processing
- H_2O Processing
- Soil Processing for H_2O

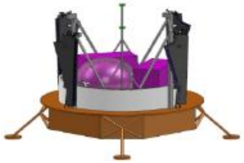
ISRU Products
- 20 to 24 mT O_2
- 6 to 7 mT CH_4
- 14 mT H_2O (used)

Life Support Backup (DRM 3)
- 4500 kg of O_2
- 3900 kg of N_2
- 23,200 kg of water (H_2O)



Consumable Depot

Preposition Consumables To Extend Traverses in Exploration Zone
- Reuse Surface Pathfinder lander design with ISRU to preposition crew consumables at sites of exploration interest away from Habitat



Increasing Usage and Architecture Impact

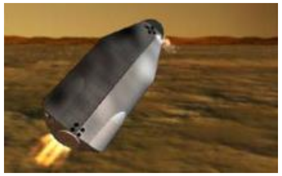
Mobile Power
- Fuel cell and reactant storage
- Amount: 1000 kg O_2 & 350 kg CH_4 per 14 day traverse

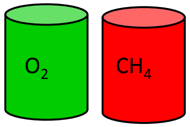
PUP

Crewed Rover

Hoppers & Reusable Landers
- Reuse previous landers to deliver cargo/crew to other destinations
- Amount: TBD based on distance and payload

Habitat Backup Power
- Fuel Cell reactants for Dust Storms
- 14.8 KW at up to 120 days
- Amount: 21 mT O_2 & 9 mT CH_4



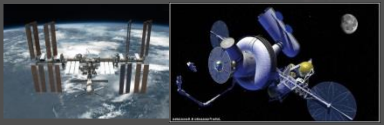


ISRU and Pathways to Mars

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

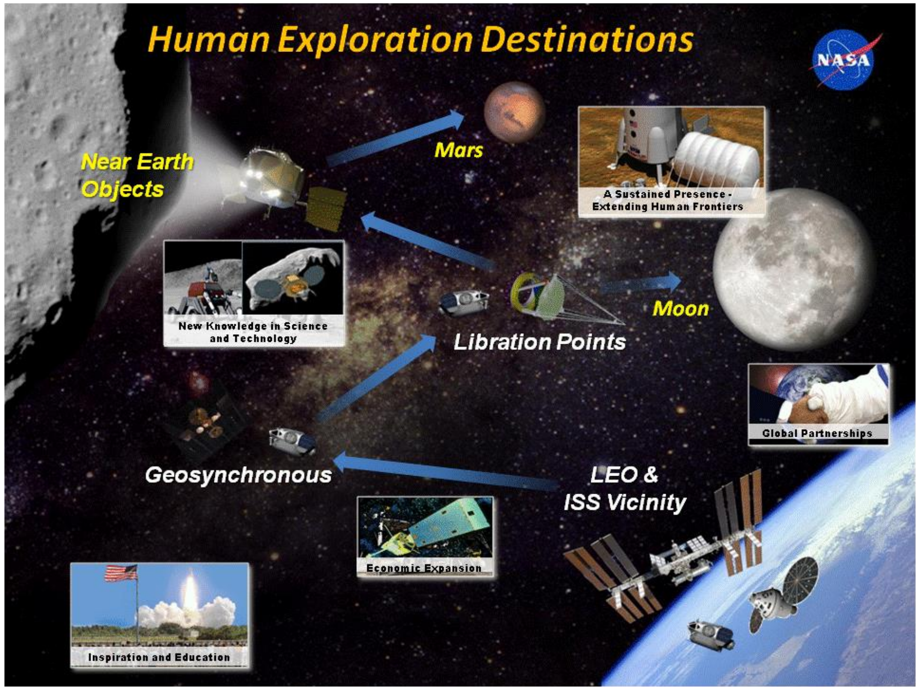
Mars

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

Multiple Pathways to Mars

Pathways are not mutually exclusive



Moon Pathway

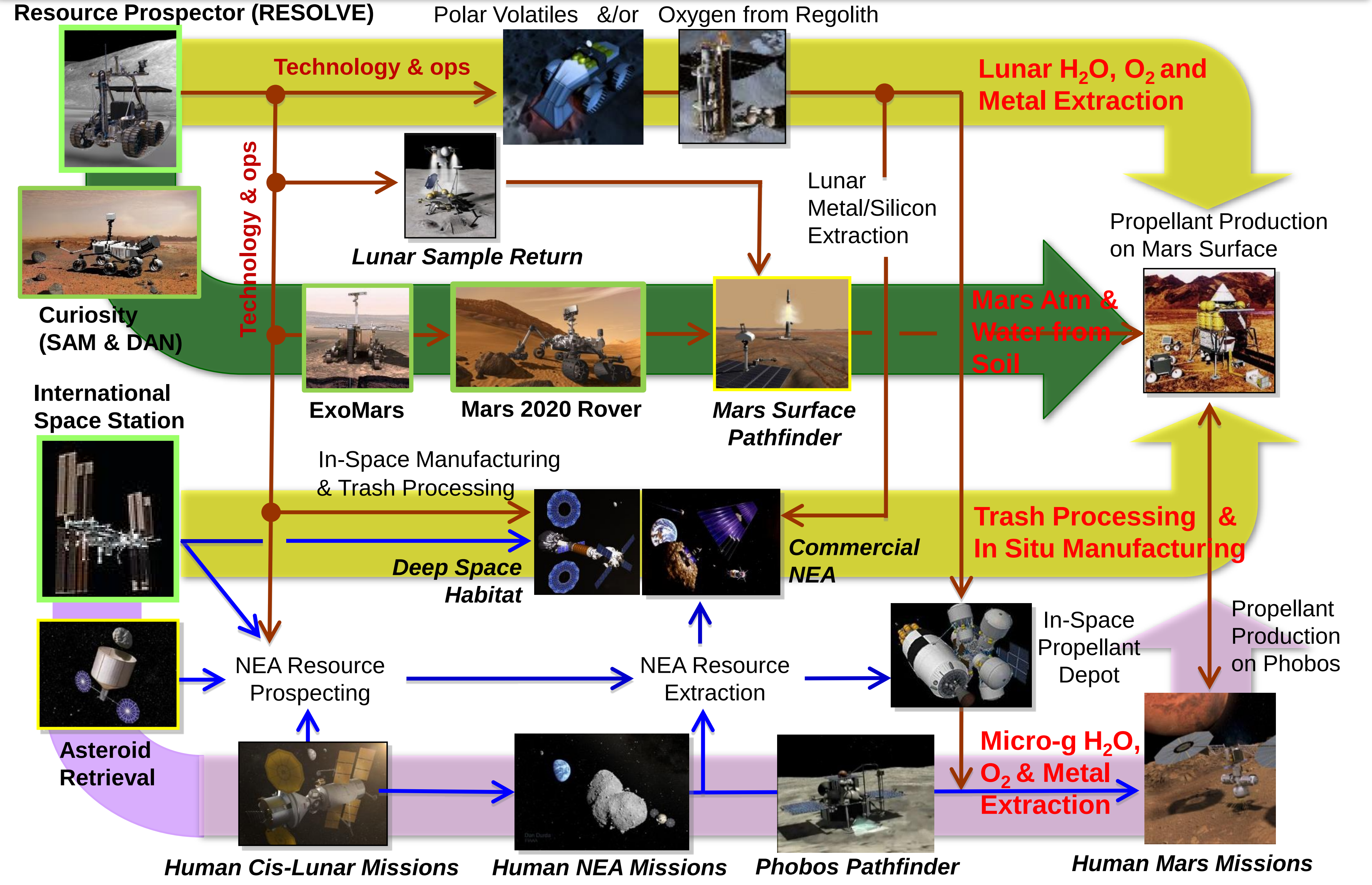
- **Use Moon as a Proving Ground for Mars Surface ISRU**
  - Regolith ice/water mining for consumables & propellants
  - Long-term operations in severe environment
  - Demonstrate common critical technologies with Mars
  - Trash processing to propellant/gas for humans in cis-lunar space
  - Demonstrate 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

🟩 = Highest Priority Path
🟨 = Mid Priority Path
🟪 = Lowest Priority Path



Resource Prospector (RESOLVE)

Polar Volatiles &/or Oxygen from Regolith

Technology & ops

Lunar H_2O, O_2 and Metal Extraction

Technology & ops

Lunar Sample Return

Lunar Metal/Silicon Extraction

Propellant Production on Mars Surface

Curiosity (SAM & DAN)

ExoMars

Mars 2020 Rover

Mars Surface Pathfinder

Mars Atm & Water from Soil

International Space Station

In-Space Manufacturing & Trash Processing

Deep Space Habitat

Commercial NEA

Trash Processing & In Situ Manufacturing

Asteroid Retrieval

NEA Resource Prospecting

NEA Resource Extraction

In-Space Propellant Depot

Propellant Production on Phobos

Micro-g H_2O, O_2 & Metal Extraction

Human Cis-Lunar Missions

Human NEA Missions

Phobos Pathfinder

Human Mars Missions

Surface Proving Ground & Pioneering: Phobos & Mars ISRU

Moon/Mars Surface Pathway

Resource Prospecting/Demonstration

- **Mars Curiosity Rover:** Surface soil mineral H_2O characterization
- **ExoMars Rover (ESA):** Surface and subsurface soil mineral & H_2O characterization
- **Resource Prospector:** Lunar polar regolith subsurface H_2O/volatile characterization and prospecting
- **Mars 2020 ISRU Demo:** O_2 from CO_2 atm., production rates targets: 0.02 kg O_2/hr

Robotic/Human Precursor-Pilot Operations

- **Mars Surface Pathfinder**
  - Primary: O_2 from CO_2 atm., production rates targets: 0.5 to 0.8 kg O_2/hr
  - Secondary: H_2O from icy or hydrated soil, CH_4 production with atm. processing
- **Mars Landing Site Surveyors - site selection precursor(s)?**
  - Site evaluation and selection for ISRU/water
    - Prospecting and terrain characterization
  - Pre-deploy assets

NEA/Phobos Pathway

Resource Prospecting/Demonstration

- **ISS Micro-g Testbeds:** Demonstration & proof-of-concepts for trash and asteroid material acquisition and processing; in-situ manufacturing
- **Phobos Pathfinder (?)**
  - Resource assessment
  - Subscale ISRU demo (?)
- **Cis-Lunar Human Exploration**
  - Trash processing to propellant/gas
  - ACRM Resource assessment; Subscale ISRU demos for acquisition and processing for water, O_2, and metals

Robotic/Human Precursor-Pilot Operations

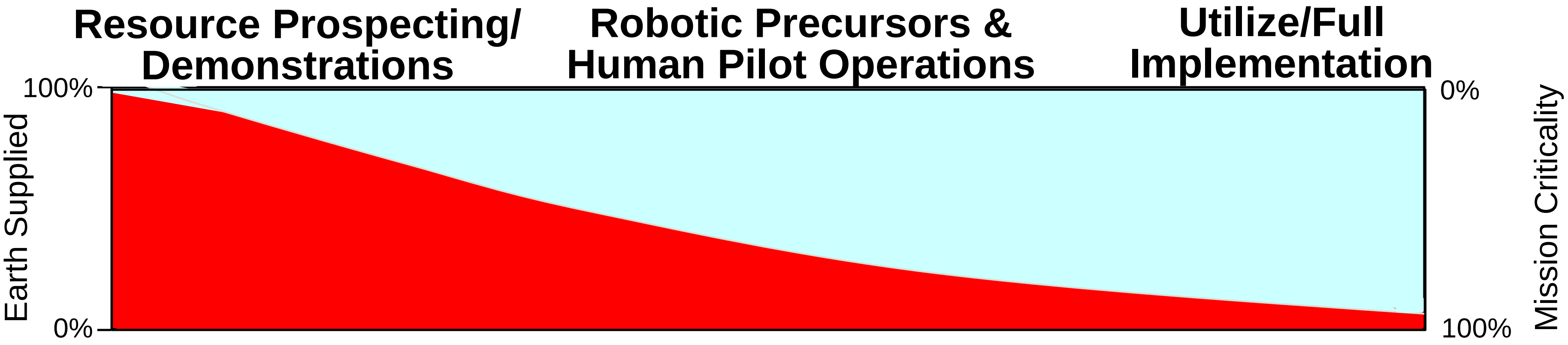
- **Phobos Human Mission**
  - LO_2/CH_4 produced from trash during outbound journey
  - Water/volatiles from local regolith
  - Shielding from regolith/water.

Pathways are not mutually exclusive

Note: **Green** = Currently Funded

Phased Approach to ISRU Architecture Incorporation

Current approach is to utilize phased approach to incorporate ISRU with minimum risk to mission success



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, micro/low-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

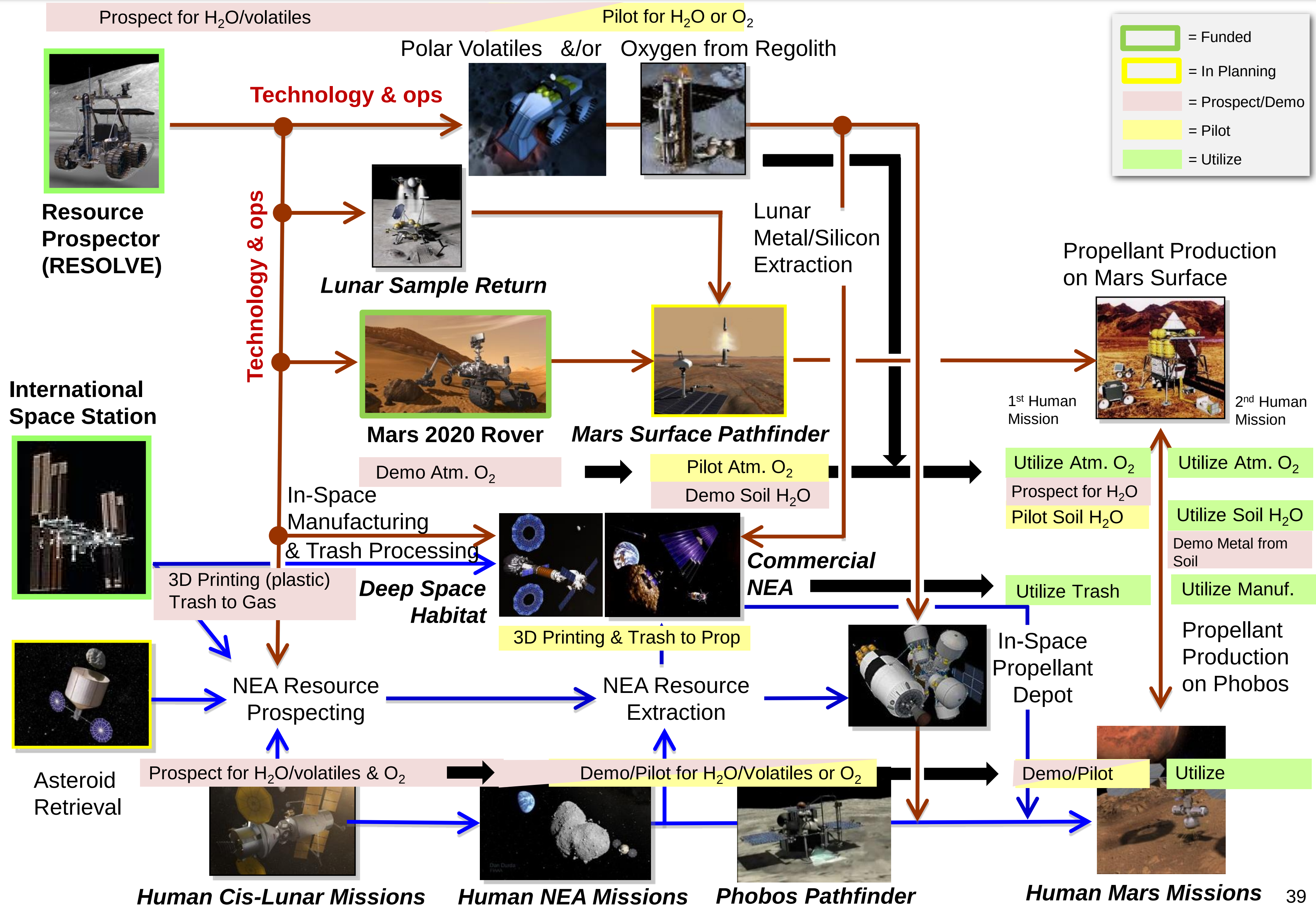
- Enhance or enable new mission capabilities
- Reduce mission risk
- Increase payload & science capabilities

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

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

- **Mars DRA 5.0**
- **Evolvable Mars Campaign**
- **Lunar outpost**

Notional ISRU Mission Evolution – With Phased Implementation



🟩 = Funded
🟨 = In Planning
▨ = Prospect/Demo
▨ = Pilot
▨ = Utilize

Prospect for H_2O/volatiles

Pilot for H_2O or O_2

Polar Volatiles &/or Oxygen from Regolith

Technology & ops

Technology & ops

Resource Prospector (RESOLVE)

Lunar Sample Return

Lunar Metal/Silicon Extraction

Propellant Production on Mars Surface

International Space Station

Mars 2020 Rover

Mars Surface Pathfinder

1st Human Mission

2nd Human Mission

Demo Atm. O_2

Pilot Atm. O_2

Demo Soil H_2O

Utilize Atm. O_2

Prospect for H_2O

Pilot Soil H_2O

Utilize Atm. O_2

Utilize Soil H_2O

Demo Metal from Soil

In-Space Manufacturing & Trash Processing

3D Printing (plastic)
Trash to Gas

Deep Space Habitat

Commercial NEA

Utilize Trash

Utilize Manuf.

3D Printing & Trash to Prop

NEA Resource Prospecting

NEA Resource Extraction

In-Space Propellant Depot

Propellant Production on Phobos

Asteroid Retrieval

Prospect for H_2O/volatiles & O_2

Demo/Pilot for H_2O/Volatiles or O_2

Demo/Pilot

Utilize

Human Cis-Lunar Missions

Human NEA Missions

Phobos Pathfinder

Human Mars Missions

ISRU Development for Multiple Pathways to Mars

ISRU Capability Development Approach

- Identify capabilities, functions, and technologies on highest priority path

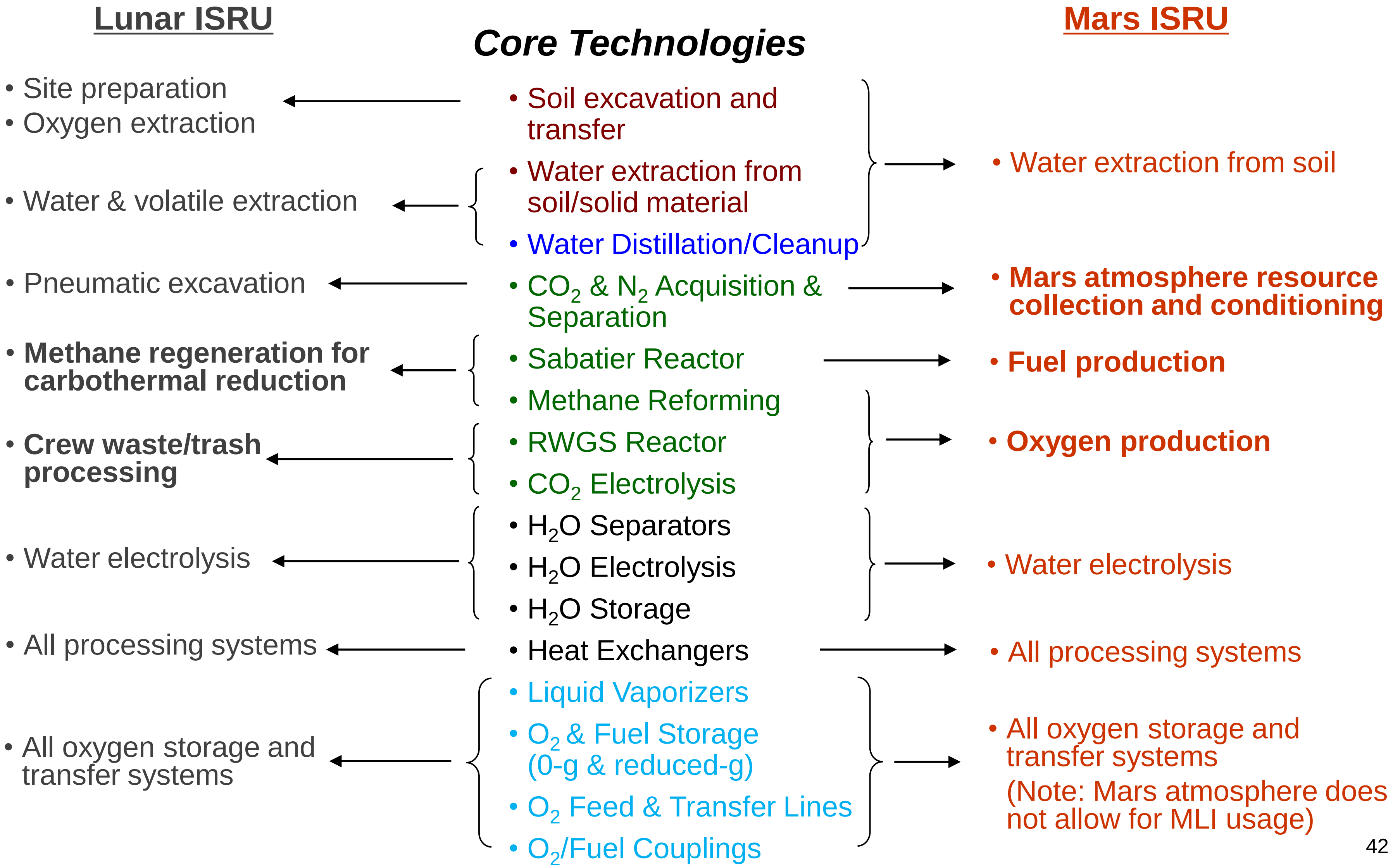
- Identify common functions and technologies for multiple destinations

- Identify common functions and technologies with other System Maturation Teams and exploration disciplines

- Identify long-term ISRU capabilities that might be needed or are architecture ‘game changers’ for lower level funding at feasibility/ demonstration level.
  - Ex. civil engineering, habitat/structure construction, conversion of *in situ* resources into feedstock for manufacturing, biological processing

Core ISRU Technologies Are Applicable To Both Moon and Mars

Lunar & Mars ISRU Share Many Common Technologies & Modules



Lunar ISRU

- Site preparation
- Oxygen extraction
- Water & volatile extraction
- Pneumatic excavation
- **Methane regeneration for carbothermal reduction**
- **Crew waste/trash processing**
- Water electrolysis
- All processing systems
- All oxygen storage and transfer systems

Core Technologies

- Soil excavation and transfer
- Water extraction from soil/solid material
- Water Distillation/Cleanup
- CO_2 & N_2 Acquisition & Separation
- Sabatier Reactor
- Methane Reforming
- RWGS Reactor
- CO_2 Electrolysis
- H_2O Separators
- H_2O Electrolysis
- H_2O Storage
- Heat Exchangers
- Liquid Vaporizers
- O_2 & Fuel Storage (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings

Mars ISRU

- Water extraction from soil
- **Mars atmosphere resource collection and conditioning**
- **Fuel production**
- **Oxygen production**
- Water electrolysis
- All processing systems
- All oxygen storage and transfer systems
  (Note: Mars atmosphere does not allow for MLI usage)

ISRU Capability-Functions vs Mission Applications & Destinations – Identify Multi-Use Functions

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

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing for Oxygen and Fuel (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen Extraction (Moon, NEO)	Material Processing for Metal Extraction (Moon, NEO)	Trash Processing to Water & Fuel
Atmosphere/Gas Collection						
Dust/Particle Filtration		X	X	X	X	X
CO_2 Capture - Separation		X		P		X
N_2 & Ar Capture - Separation						
Gas Processing						
CO_2 Conversion into $CO\text{-}O_2$		X				
CO/CO_2 Conversion into $H_2O\text{-}CH_4$		P		P	P	X
Gas-Gas Separation & Recycling		X	P	P	P	X
Water Processing						
Water Capture	X		X	X		X
Water Cleaup - Purity Measurement			X	X		X
Water Electrolysis		P	X	P		X
Regenerative Dryers		P	X	P		X
Support Systems						
Extended Polar Operation Power Systems	P		P	P	P	
Extended Polar Operation Thermal Systems	P		P	P	P	
Mobility	X		X	X	X	
Cryogenic Liquefaction, Storage, and Transfer		X		X		P
Autonomous Operation	X	X	X	X	X	

X = Needed; P = Possible need

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

ISRU Technology Development Options

	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metal (Moon, Mars, NEO)	Trash Processing for 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					
Crushing			P	X	P
Size Sorting				P	
Beneficiation/Mineral Seperation				P	
Solid/Gas Processing Reactor	X		X	X	X
Solid/Liquid Processing Reactor				P	
Volatile Cleanup			X	X	X
Extended Operation Power Systems			P	P	
Extended Operation Thermal Systems			P	P	
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_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

X = Needed; P = Possible Need

Technology Options

- Auger
- Pneumatic Transport
- Bucketwheel/Bucketdrum
- Scoop/Clamshell
- Percussive Scoop

- Auger
- Percussive Scoop

- Gas Chromatograph
- Mass Spec
- Laser Diode
- IR Spectrometer

- Fluidized Bed (with or w/o assisted mixing)
- Cyclone Reactor
- Rotating/Centrifugal Reactor
- Auger Reactor
- Ionic Liquid Reactor
- Carbothermal Reactor
- Molten/Molten-Salt Reactor
- Supercritical Water Reactor

Heating Method
- Resistive Heater
- Microwave
- Inductive Heating
- Solar

- Membrane Separator
- CO_2 Freezer Pump
- Rapid Cycle Adsorption Pump
- Solid Oxide Electrolysis
- Reverse Water Gas Shift
- Sabatier
- Ionic Liquid Reactor
- Electrochemical Reactor

- PEM-based Non-Flow Through
- Solid Oxide Electrolysis
- Freezing
- Adsorption

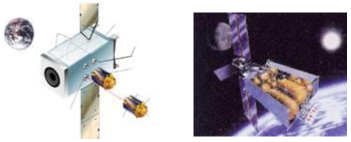
Core Technologies Are Applicable To Multiple Applications & Destinations

Maximize Benefits, Flexibility, & Affordability

In-Situ Production Of Consumables for Propulsion, Power, & ECLSS

Fuel Cell Power for Spacecraft, Rovers & EVA

0-g & Surface Propellant Depots



Core Technologies

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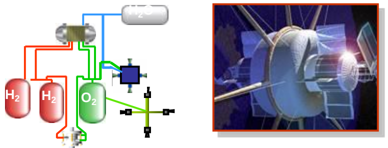
- H_2O Separators
- H_2O Electrolysis
- Fuel Cells
- H_2O Storage
- Heat Exchangers
- Liquid Vaporizers
- O_2 & Fuel Storage (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings
- O_2/Fuel Igniters & Thrusters

Life Support Systems for Habitats & EVA

Habitat, EVA, and radiation shielding

Water – Gaseous H_2/O_2 Based Propulsion



Station keeping, depots, integrated power

Non-Toxic O_2-Based Propulsion

Launch vehicle & human/robotic landers

Conclusion

Takeaways

- ISRU has the potential to be a disruptive technology that will change the way we explore space
  - ➢ Earlier/longer development required to demonstrate ISRU capability is viable (way before mission PDR)
- ISRU is necessary to enable a sustainable presence in space and on Mars
  - Fewer logistics and supplies need to be launched from Earth
  - Autonomy and reusability for ISRU reduces operational dependency on Earth
- Multiple pathways exist to prospect, test, and utilize ISRU technologies “on the way” to Mars
  - Direct to Mars - Carbon dioxide/Mars atmosphere processing for oxygen
  - Water prospecting, regolith acquisition and processing, and resource storage, on the Moon
  - Trash recycling on ISS, and micro-g ISRU (water, oxygen, building materials) at NEAs, and at Phobos
- ISRU has numerous benefits, but also requires up-front investment that pays off over the life cycle of a mission
- Common technologies and capabilities have been identified for ISRU at different destinations (pathways) and other exploration systems to reduce cost and risk
  - ISRU and common technologies are being developed today
- ISRU has potential to provide the first commercial market in cis-lunar space and beyond