EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LIVE: In Situ Resource Utilization (ISRU)
NASA Space Technology Mission Directorate

STMD welcomes feedback on this presentation. Please visit https://techport.nasa.gov/framework/feedback if you have any questions or comments regarding this presentation.

LIVE: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities

Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface*

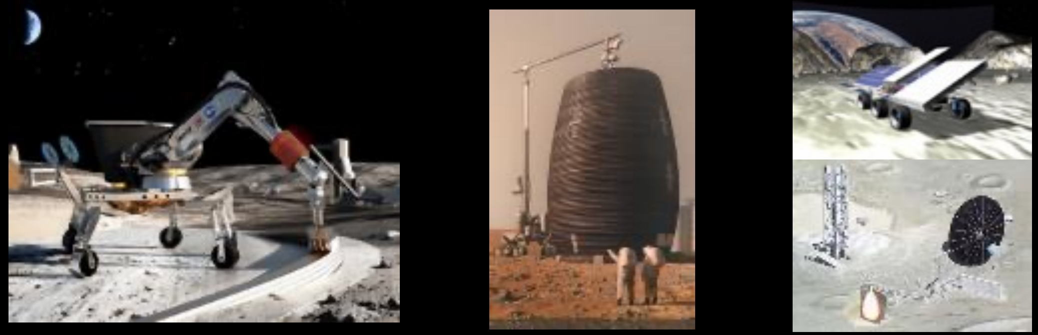
COMMERCIAL SCALE WATER, OXYGEN, METALS & COMMODITY PRODUCTION

- Lunar resources mapped at meter scale for commercial mining
- 10’s of metric tons of commodities per year for initial goal commercial usage
- Scalable to 100’s to 1000’s metric tons per year

COMMODITIES FOR HABITATS & FOOD PRODUCTION

- Water, fertilizers, carbon dioxide, and other crop growth support
- Crop production habitats and processing systems
- Consumables for life support , EVAs, and crew rovers/habitats for growing human space activities

IN SITU DERIVED FEEDSTOCK FOR CONSTRUCTION, MANUFACTURING, & ENERGY



- Initial goal of simple landing pads and protective structures
- 100’s to 1000’s metric tons of regolith-based feedstock for construction projects
- 10’s to 100’s metric tons of metals, plastics, and binders
- Elements and materials for multi-megawatts of energy generation and storage
- Recycle, repurpose, and reuse manufacturing and construction materials & waste

COMMODITIES FOR COMMERCIAL REUSABLE IN-SPACE AND SURFACE TRANSPORTATION AND DEPOTS

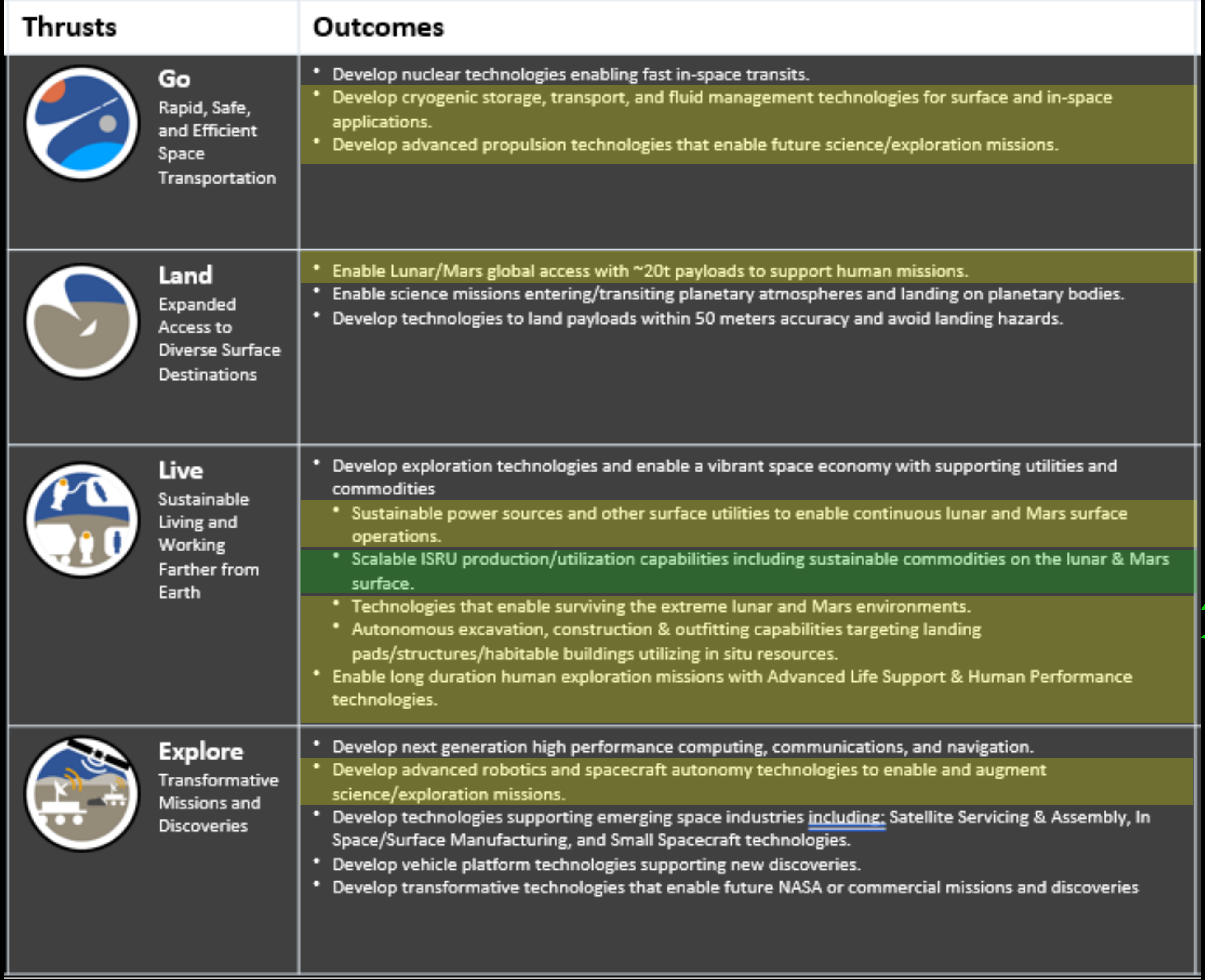
- 30 to 60 metric tons per lander mission
- 100’s to 1000’s metric tons per year of for Cis-lunar Space
- 100’s metric tons per year for human Mars transportation

All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.

*Commodities are items and consumables that can be eventually sold

IN SITU RESOURCE UTILIZATION (ISRU) INTERFACES WITH MULTIPLE STRATEGIC OUTCOMES AND REQUIRE SUPPORT FROM OTHER PT/SCLTS

ISRU Outcome: Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.



Thrusts	Outcomes
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live
Sustainable Living and Working Farther from Earth
	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries

Cryogenic Fluid Management –liquefaction, storage, and transfer

Advanced Propulsion - Provide propellant to reduce landed mass; increase ascent vehicle capability; reusability

Entry Descent and Landing - Ascent Vehicle design

Advanced Power Systems – Receive power; provide fuel cell consumables; alternative thermal storage; common technologies

Advanced Thermal Management – 10's KW thermal heat rejection; shutdown or operation in lunar night and shadowed regions

Autonomous Excavation, Construction, & Outfitting
Receive/remove regolith; provide resource information and manufacturing/construction commodities; common technologies

Advanced Habitation Systems– Provide consumables; receive waste & trash; common technologies

Autonomous Systems & Robotics – Mobile platforms; Receive control and monitoring of complex ISRU operations

In Situ Resource Utilization (ISRU) Capability – *'Prospect to Product'*

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create commodities* for robotic and human exploration and space commercialization

Destination Reconnaissance & Resource Assess

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

Resource Acquisition, Isolation, & Preparation

Atmosphere constituent collection, and soil/material collection via drilling, excavation, transfer, and/or manipulation before Processing

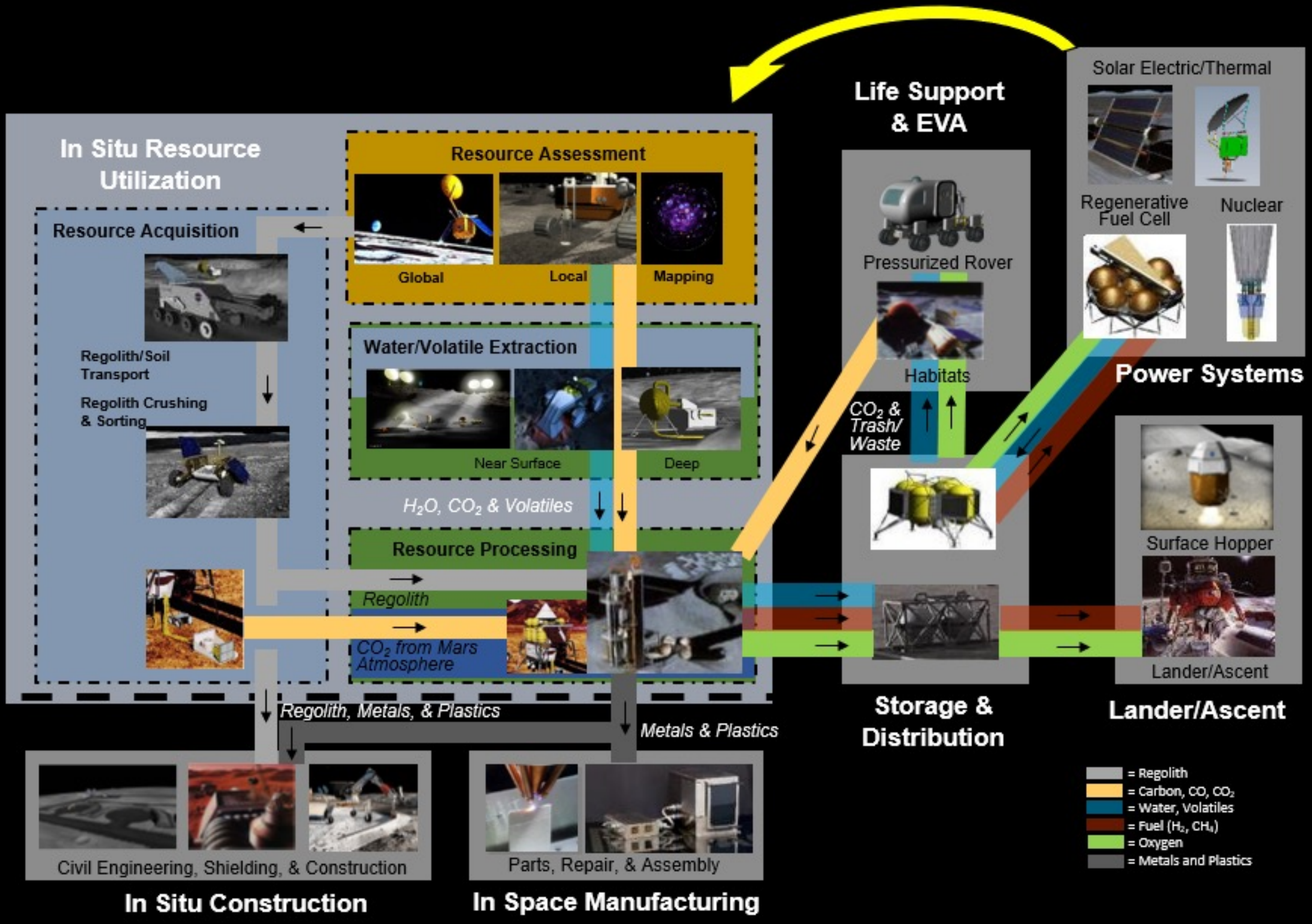
Resource Processing

Chemical, thermal, electrical, and or biological conversion of acquired resources and intermediate products into

- Mission Consumables
- Feedstock for Construction & Manufacturing

Water/Volatile Extraction

A subset of both Resource Acquisition and Processing focused on water and other volatiles that exist in extraterrestrial soils



- **ISRU is a capability involving multiple disciplines and elements to achieve final products**
- **ISRU does not exist on its own. It must link to users/customers of ISRU products**

*Commodities are items and consumables that can be eventually sold

ISRU Functional Breakdown And Flow Diagram

Destination Reconnaissance and Resource Assessment

- Site Imaging/Terrain Mapping
- Instruments for Resource Assessment
- Orbital Resource Evaluation
- Local Surface Resource Evaluation
- Resource/Terrain/Environment Data Fusion and Analyses

Resource Acquisition, Isolation, and Preparation

- Resource Excavation & Acquisition
- Resource Preparation before Processing
- Resource Transfer
- Resource Delivery from Mine Site and Removal

Resource Processing for Production of Mission Consumables

- Resource Storage and Feed To/From Processing Reactor
- Regolith Processing to Extract Oxygen
- Regolith Processing to Extract Water
- Carbon Dioxide Processing
- Water Processing
- Instrumentation to Characterize Processing Performance
- Product/Reactant Separation
- Contaminant Removal from Reagents/Products

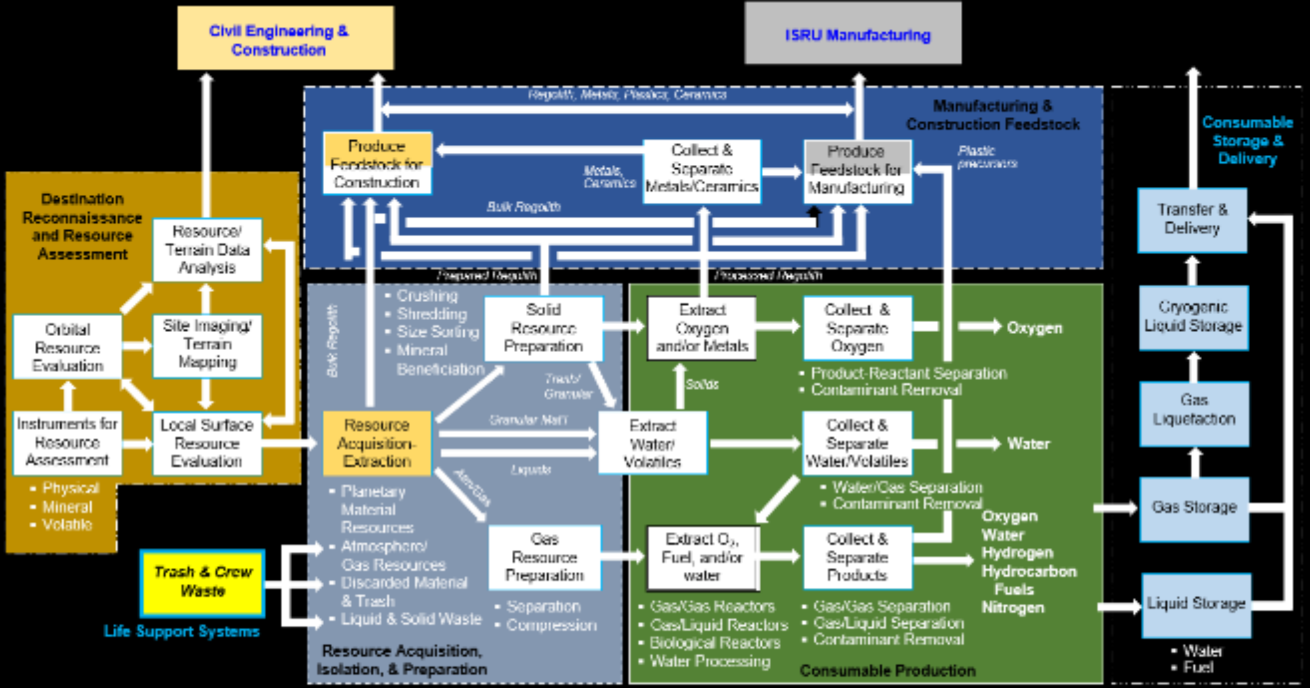
Resource Processing for Production of Manufacturing and Construction Feedstock

- In Situ Excavation and Movement for Construction
- Resource Preparation for Construction Feedstock
- Material transfer
- Resource Processing to Extract Metals/Silicon
- Resource-Trash/Waste Gas Processing to Produce Methane/Plastics

Cross Cutting

- Planetary Simulants for Test & Verification
- Planetary Regolith/Environment Test Chambers

- **Functional Breakdown and Flow Diagram used to understand:**
  - Technology State of the Art and gaps
  - Connectivity Internally and with other disciplines
  - Influence of technologies on complete system and other functions
- **ISRU functions have shared interest w/ Autonomous Excavation, Construction, & Outfitting (AECO)**
  - Destination Reconnaissance
  - Resource Excavation & Delivery
  - Construction Feedstock Production



ISRU Must Operate as Part of A Larger Architecture

P = Provided to ISRU
S = Supplied by ISRU
Italic = Other Disciplines

- Architecture elements must be designed with ISRU product usage in mind from the start to maximize benefits
- Infrastructure capabilities and interdependencies must be established and evolve with ISRU product users and needs
  - Transition from Earth-supplied to ISRU-supplied
  - Guided by overarching Site Master Plan

Power:
- Generation, Storage, & Distribution (P)
- ISRU-derived electrical /thermal (S)

Advanced Power Systems

ISRU

Coordinated Mining Ops:
Areas for:
i) Excavation
ii) Processing
iii) Tailings
iv) Product Storage

In situ Instruments/Sensors
Autonomous Systems
Adv. Thermal Management

Transportation to/from Site:
- Delivery (P)
- Propellants & Depots (S)

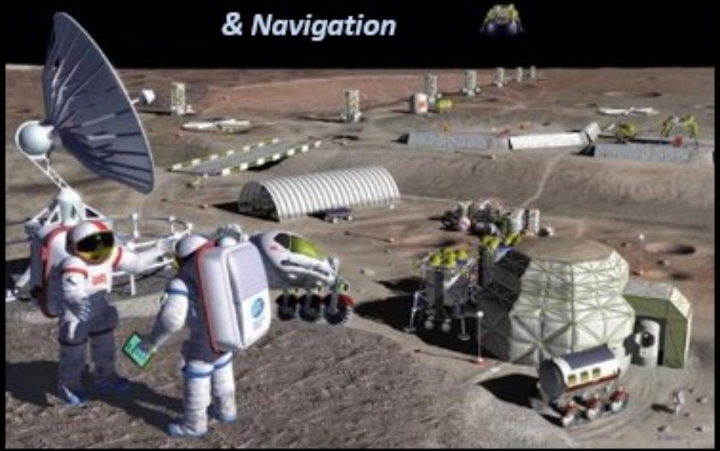
Advanced Propulsion
Entry Descent and Landing

Commodity Storage and Distribution:
- Water & Cryogenic Fluids (CFM)
- Manufacturing & Construction Feedstock

Cryogenic Fluid Management
Autonomous Systems & Robotics
Autonomous Excavation, Construction, & Outfitting

Communications & Navigation (P)
- To/From Site
- Local

Adv. Communication & Navigation

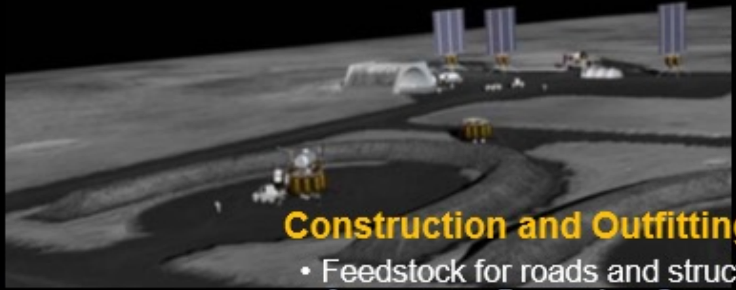


Maintenance & Repair

Logistics Management
- Replacement parts (P)
- Feedstock (S)

In Space/Surface Manufacturing

Living Quarters & Crew Support Services
- Water, O_2, H_2, Gases (S)
- Trash/waste (P)
- Nutrients(S)



Construction and Outfitting
- Feedstock for roads and structures (S)

Autonomous Excavation, Construction, & Outfitting
Autonomous Systems & Robotics

Moon to Mars (M2M) Blueprint Objectives:

ISRU Objectives Traceability Matrix

🟩 = Science: Lunar/Planetary Science (LPS), Science-Enabling (SE), Applied Science (AS)
🟪 = Infrastructure: Lunar Infrastructure (LI), Mars Infrastructure (MI)
🟦 = Transportation and Habitation (TH)
🟥 = Operations (OP)
🟧 = Recuring Tenets (RT)
⬆ = Key ISRU M2M Objectives

Resource Assessment

AS-3^{LM} ⬆	**Characterize accessible lunar and martian resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.**
OP-3^{LM} ⬆	**Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.**
LPS-3^{LM}	Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport**, and sequestration of lunar and martian volatiles**.
TH-7^{M}	Develop systems for crew to explore, operate, and live on the martian surface to address key questions with respect to science and **resources.**
SE-3^{LM}	Develop the capability to **retrieve core samples of frozen volatiles** from permanently shadowed regions on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth.

ISRU and Usage

LI-7^{L} ⬆	**Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.**
LI-8^{L}	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing **maximizing the use of in-situ resources**, and support systems needed for continuous human/robotic presence.
MI-4^{M} ⬆	**Develop Mars ISRU capabilities to support an initial human Mars exploration campaign.**
OP-11^{LM} ⬆	**Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.**
TH-3^{L}	Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit **with scalability to continuous presence**; conducting scientific and industrial utilization as well as Mars analog activities.

Responsible ISRU

SE-7^{LM}:	Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as martian recurring slope lineae, to enable future high-priority science investigations.
OP-12^{LM}	Establish procedures and systems that will minimize the disturbance to the local environment, **maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (**and from the lunar surface in the case of Mars) to be used during exploration
RT-6	**Responsible Use:** conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space

These are the Recurring Tenets; themes common across all blueprint objectives.

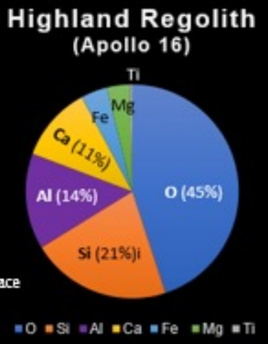
RT-1	**International Collaboration:** partner with international community to achieve common goals and objectives
RT-2	**Industry Collaboration:** partner with U.S. industry to achieve common goals and objectives
RT-3	**Crew Return:** return crews safely to Earth while mitigating adverse impacts to crew health
RT-4	**Crew Time:** maximize crew time available for science and engineering activities within planned mission durations
RT-5	**Maintainability and Reuse:** when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence
RT-6	**Responsible Use:** conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space
RT-7	**Interoperability:** enable interoperability and commonality (technical, operations and process standards) among systems, elements, and crews throughout the campaign
RT-8	**Leverage Low Earth Orbit:** leverage infrastructure in Low Earth Orbit to support M2M activities
RT-9	**Commerce and Space Development:** foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation

Superscript text indicates the applicability to Lunar (L), Martian (M) or both (LM).

Time and Spatial Evolution of Lunar Resources and Commodities for Commercial and Strategic Interests

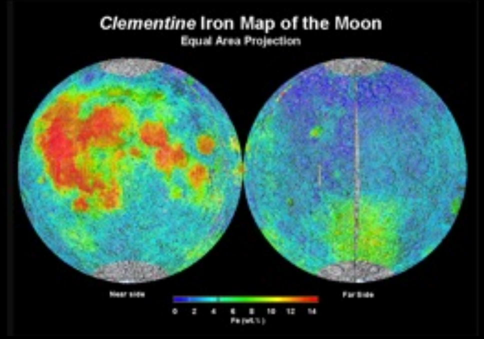
- ISRU starts with the easiest resources to mine, requiring the minimum infrastructure, and providing immediate local usage
- The initial focus is on the lunar South Pole region (highland regolith and water/volatiles in shadowed regions)
  - ISRU will evolve to other locations, more specific minerals, more refined products, and delivery to other destinations

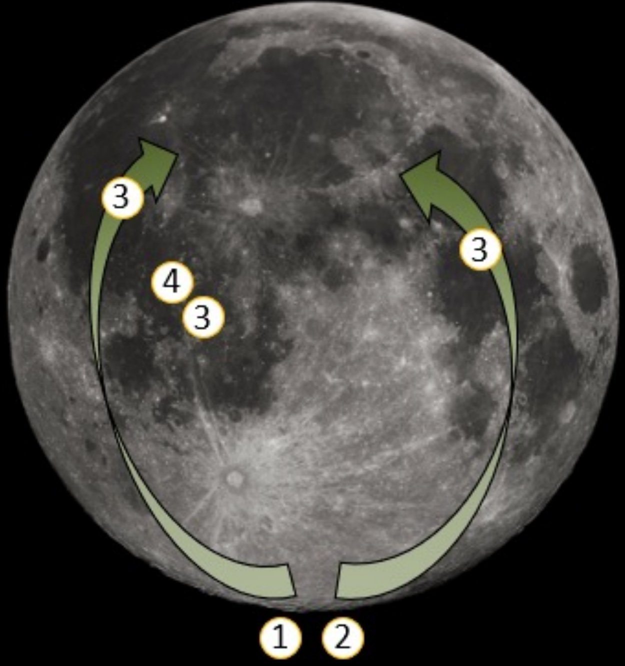
1. Polar Highland Regolith
(Oxygen, Aluminum, Silicon)



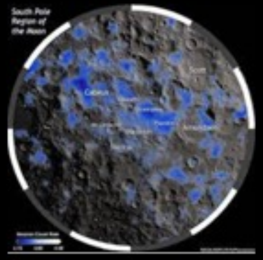
from Planetary and Space Science, Vol. 74,

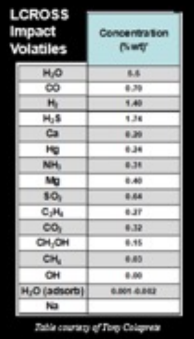
3. Ilmenite and Pyroclastic Glass
(Iron, Titanium, Solar Wind Volatiles)





2. Polar Water/Volatiles

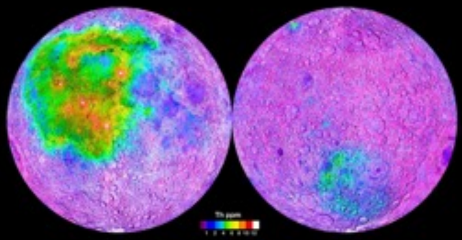




LCROSS Impact Volatiles	Concentration (% wt)
H_2O	5.6
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

4. Rare Earth Elements & Thorium



Indication of where KREEP is
(Procellerum KREEP Terrane)

Commodities

- **Oxygen**
- **Water**
- **Bulk & Refined Regolith**
- **Raw & Refined Metals (Al, Fe, Ti)**
- **Silicon and Ceramics**
- **Construction Feedstock**
- **Manufacturing Feedstock**
- **Fuels, Plastics, Hydrocarbons**
- **Food/Nutrient Feedstock**

Lunar ISRU Commodities:
Polar Water, Oxygen from Regolith, and Feedstocks/Precursors

- **Water (and Volatiles) from Polar Regolith**
  - Form, concentration, and distribution of Water in shadowed regions/craters is not known
    - Technologies & missions in work to locate and characterize resources to reduce risk for mission incorporation
  - Provides 100% of chemical propulsion propellant mass
  - Polar water is "Game Changing" and enables long-term sustainability
    - Strongly influences design and reuse of cargo and human landers and transportation elements
    - Strongly influences location for sustained surface operations

- **Oxygen/Metal from Regolith**
  - Lunar regolith is >40% oxygen (O_2) by mass
    - Polar highland regolith: mostly anorthosite rich in aluminum and silicon; poor in iron
    - Equatorial mare regolith: regions of high iron/titanium, KREEP, and pyroclastic glasses
  - Technologies and operations are moderate risk from past work and can be performed anywhere on the Moon
  - Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth); O_2 for EVA, rovers, Habs.
  - Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions

- **Manufacturing & Construction Feedstock**
  - Bulk or refined regolith (size sorted/mineral beneficiation) forms the bulk of the construction feedstock
  - Metals and slag from oxygen extraction can be used or modified as feedstock
  - Chemical and biological processing to produce binders and further refine construction materials
  - ➢ Requires close ties to In Space Manufacturing (ISM) and Autonomous, Excavation, Construction and Outfitting (AECO)

- **Support for Plant/Food/Nutrient Production**
  - Bulk or refined regolith (size sorted, mineral beneficiation, milled, treated) for plant growth media
  - Chemical and biological processing (esp. of carbon/water) of wastes and in situ resources to produce nutrient and food precursors
  - ➢ Requires close ties to Life Support Systems

Plan to Achieve ISRU Outcome

Scalable ISRU production/utilization capabilities including ***sustainable commodities*** *on the lunar & Mars surface*

- **Enable Industry to Implement ISRU for Artemis, Sustained Human Presence, and Space Commercialization**
  - Define Initial and Long-term Customer Needs for ISRU-derived Products
    - Work within NASA and International Partners: Artemis elements, Moon/Mars Surface Architecture, and Critical Systems (Life Support & Food Production, Propulsion, Manufacturing, Construction)
    - Utilize Lunar Surface Innovation Consortium and work with Terrestrial/Space Industry to define near-term needs and to lay the foundation for long-term lunar economic development

  - Advance ISRU technologies and systems for lunar missions by utilizing NASA solicitations, public private partnerships, internal/external investments
    - Perform and support extensive ground development, low/micro-g flights, and integration/testing of hardware and systems
    - Coordinate requirements, development, and implementation of infrastructure required for ISRU operations (Power, Product Storage, Comm & Nav., Excavation and Construction, etc.)

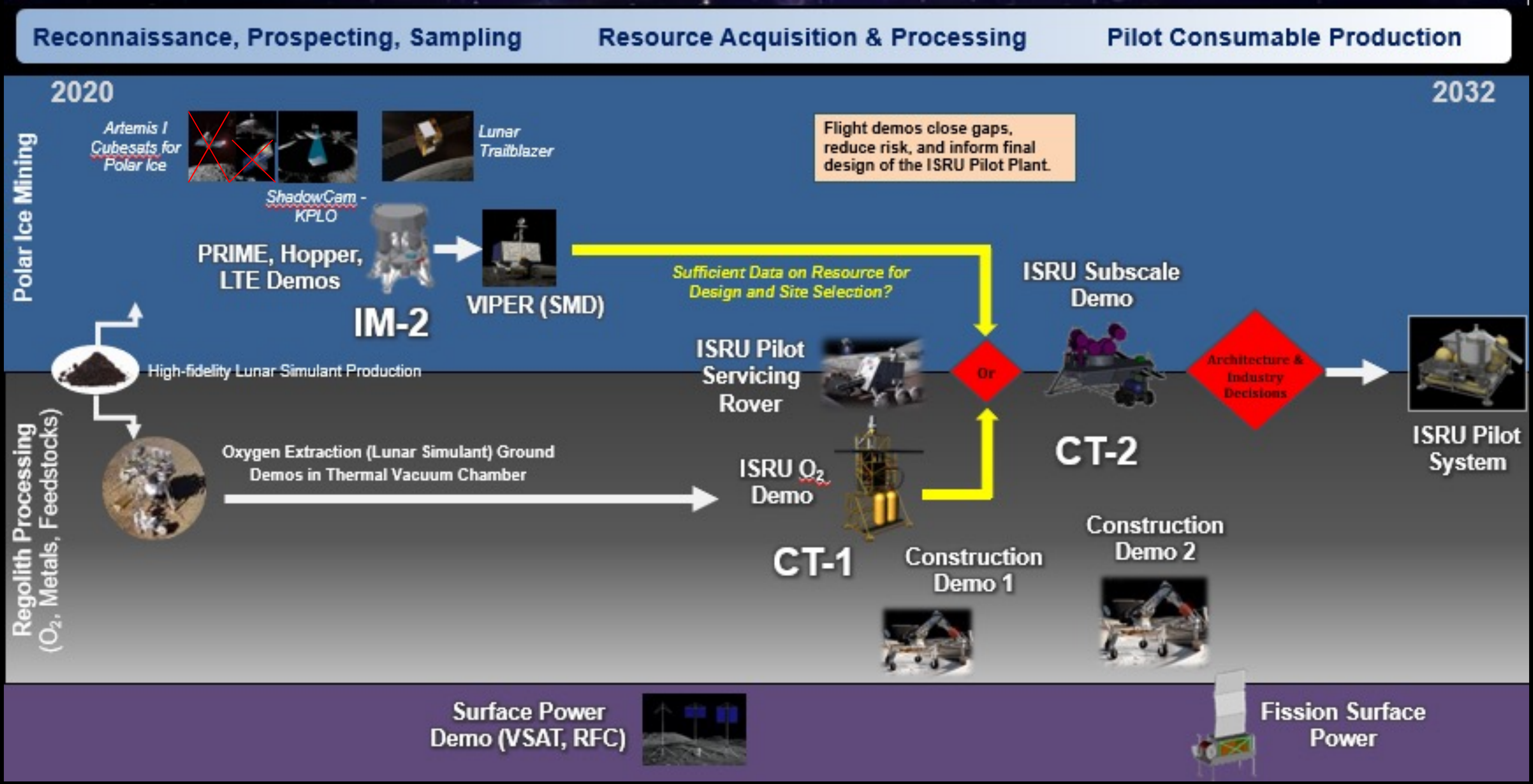
  - Reduce Risk and Promote Investment in ISRU Systems and Products
    - Provide to industry key and enabling NASA capabilities and resources to include:
      - Perform fundamental research and technology development, both high TRL (near term) and low TRL (distant)
      - Information, facilities, and technologies (technology transfer)
      - Foster and support or lead system modeling/analysis, integration, and analog and environmental testing of diverse technologies from multiple companies and partners
    - Support data buys for lunar resource understanding and ISRU technologies/operations
    - Perform and support lunar resource assessment and technology demonstrations (CLPS, HLS, Int'l Partner, Industry)

- **Promote Industry-led ISRU Development thru End-to-End ISRU Production of Commodities (i.e. Pilot Plant)**
  - Production at sufficient scale to eliminate risk of Full-scale system
  - Initially use ISRU-derived commodity in non-mission critical applications (life support, hopper propellant, etc.)

- **ISRU must be demonstrated on the Moon before mission-critical applications are flown**
  - Utilize lunar flight demonstrations and Pilot Plant operations to break 'chicken and egg' cycle
  - Conduct prospecting missions to locate predicted water/ice reserves proximal to potential base camps.

ISRU Path to Full Implementation & Commercialization*

**Proposed missions and timeline are contingent on NASA appropriations, technology advancement, and industry participation, partnerships, and objectives*



Full-scale implementation & Commercial Operations

This requires transition and 'Pull' from STMD to ESDMD and Industry

(next chart)

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
  - Regolith Processing and O_2/Metal Path supports Surface Construction activities and demonstrations as well
- Ground development of multiple critical technologies in both pathways underway to maximize success and industry involvement
- Resource assessment missions to obtain critical data on mineral and water/volatile resources have started
  - Significant uncertainty if existing missions are sufficient to define resources for design and site selection

Mid-Term Envisioned Future:
Evolve from STMD Demonstrations to Sustained Lunar Surface Operations

STMD Leads *Individual* Technology Development and Flight Demonstrations

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.


ISRU Demo & Pilot Plant


ISRU Pilot Excavator



Precision Landing (SPLICE) & Plume Surface Interaction

Cryo Fluid Management TP & Flight Demos

Autonomous Robotics, LIDAR, and Navigation

In Situ Construction Demos


Vertical Solar Array Technology (VSAT)


Power Beaming


40 KWe Nuclear Reactor Demo

Regenerative Fuel Cell Power Demo

ESDMD Evolves STMD Capabilities into Sustained Artemis Base Camp Infrastructure and Commercial Operations

OP-11^{LM}	**Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.**
TH-3^{L}	Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit **with scalability to continuous presence**; conducting scientific and industrial utilization as well as Mars analog activities.

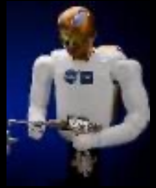
Large Scale Power Generation & Distribution


Complex, Multi-Element ISRU Operations

Landing Pad & Infrastructure Construction


Cryogenic Consumables & Propellant Depots

Human and Robotic Maintenance & Repair

Offloading, Deployment, and Repurposing


Lander, Habitat, and Surface Vehicle Servicing

In Situ Propellant & Consumable Production

Phases of Evolution and Use – *Need to Plan for Scale-up from the Start*

Demonstrate, Build Confidence, Increase Production and Usage

NPS = Near Permanent Sunlight

PSR = Permanently Shadowed Region

10 to 50 mT Range for Initial Full-Scale Production

	Demo Scale	Pilot Plant	Crewed Ascent Vehicle[1]	Full Descent Stage[1]	Lockheed Martin[6]		Dynetics[6] Single Stage/ Drop Tanks	Single Stage to NRHO[2]	Human Landing System - Starship[7]	Human Mars Transportation[3]	Commercial Cis-Lunar Transportation[4]
			3 Stage Arch to NRHO		2 Stage	Single Stage					
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	per mission	per mission	per mission	per mission	per mission	per year	per year
Demo/System Mass[5]	10's kg to low 100's kg	1 mt O_2 Pilot 1.3 – 2.5 mt Ice Mining	1400 to 2200 kg	2400 to 3700 kg				Not Defined		Not Defined	29,000 to 41,000 kg
Amount O_2	10's kg	1000 kg	4,000 to 6,000 kg	8,000 to 10,000 kg	10,000 kg	33,000 kg	32,000 kg	30,000 to 50,000 kg	120,000 (NRHO) 440,000 (Earth)	185,000 to 267,000 kg	400,000 to 2,175,000 kg
Amount H_2	10's gms to kilograms	125 kg		1,400 to 1,900 kg	2,000 kg	7,000 kg	Methane Fuel	5,500 to 9,100 kg	Methane Fuel	23,000 to 33,000 kg	50,000 to 275,000 kg
Power for O_2 in NPS	100's W	5 to 6 KW	20 to 32 KW	40 to 55 KW				N/A		N/A	N/A
Power for H_2O in PSR	100's W	~2 KW		~25 KW				14 to 23 KW			150 to 800 KW
Power for H_2O to O_2/H_2 in NPS		~6 KW		~48 KWe				55 to 100 KWe			370 to 2,000 KWe

[1] Estimates from rocket equation and mission assumptions

[2] Estimates from J. Elliott, "ISRU in Support of an Architecture for a Self-Sustained Lunar Base "

[3] Estimate from C. Jones, "Cis-Lunar Reusable In-Space Transportation Architecture for the Evolvable Mars Campaign"

[4] Estimate from "Commercial Lunar Propellant Architecture" study

[5] Electrical power generation and product storage mass not included

[6] APL Lunar Surface Innovation Consortium Suppy-Demand Workshop, 9/17/2020

[7] Calculations/Assumptions from Publicly Available Data

- Table uses best available studies and commercial considerations to guide development requirements/FOMs
- Table provides rough guide to developers and other surface elements/Strategic Technology Plans for interfacing with ISRU

NASA ISRU Capability State of the Art and Current Work

Resource Assessment – Flight Development (TRL 4-6)
- Multiple instruments under development by SMD and STMD for resource collection and assessment
- Instruments to be flown on CLPS missions – PRIME-1 and VIPER for lunar ice characterization

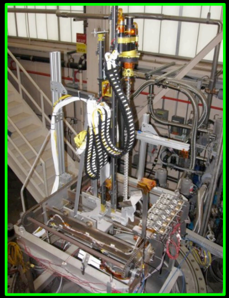
Water Mining – Proof of Concept (TRL 2/3)
- 3 water/ice mining approaches and 6 water extraction technologies examined
- Challenges: Space Robotic, Break the Ice Lunar

Oxygen Extraction from Regolith – Mare Regolith (TRL 4/5)
- Two Hydrogen Reduction and one Carbothermal Reduction systems built and tested at sub-Pilot scale; terrestrial operations, non-flight mass/power, mare regolith, days/weeks operation ('08 & '10)
- New work on combined Hydrogen Reduction/Carbothermal Reduction under laboratory conditions

Oxygen/Metal Extraction from Regolith – Highland Regolith (TRL 2/4)
- Carbothermal Reduction (TRL 3/5)
- Molten Regolith Electrolysis (TRL 3/4); Molten Salt Electrolysis-ESA (TRL 3/4)
- Ionic Liquid Reduction (TRL 2/3)
- Low TRL Concepts: Hydrogen Plasma Reduction, Vapor Phase Pyrolysis, Bio-Mining, Alkaline Reduction

Lunar Regolith Processing Support
- Regolith column sealing and Regolith reactor valving
- Regolith transfer and conveyance
- Regolith size sorting & mineral beneficiation; Ilmenite beneficiation demonstrated on lunar-g aircraft
- Solar concentrators and solar energy transmission
- 9 water electrolysis projects in 3 different types (PEM, SOE, Alkaline)

Construction Feedstock (Low TRL: 2-4)
- Feedstock (blends of simulant and plastic) used in manufacturing & construction lab. demonstrations
- Mars concrete and soil/binders demonstrated: ACME & 3D Hab, Construction Centennial Challenge
- Size sorted lunar simulants being used for sintering construction tests
- 3D printer with simulant feedstock was tested on the ISS in the Additive manufacturing Facility
- Trash-to-Gas as start to conversion to fuels/plastics

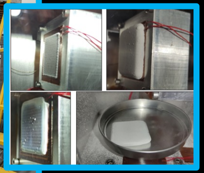



PRIME-1

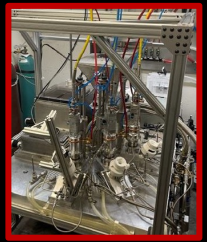

VIPER


Thermal Corer

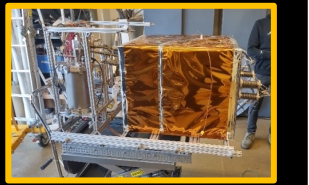

Lunar Auger Dryer ISRU (LADI)


Water Capture


Open Reactor Feasibility Testing


Carbothermal Reduction

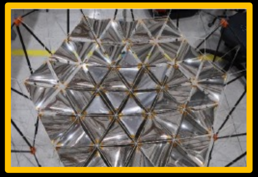

Molten Regolith Electrolysis


SOE Water Electrolysis


MMOST Size Separation & Beneficiation

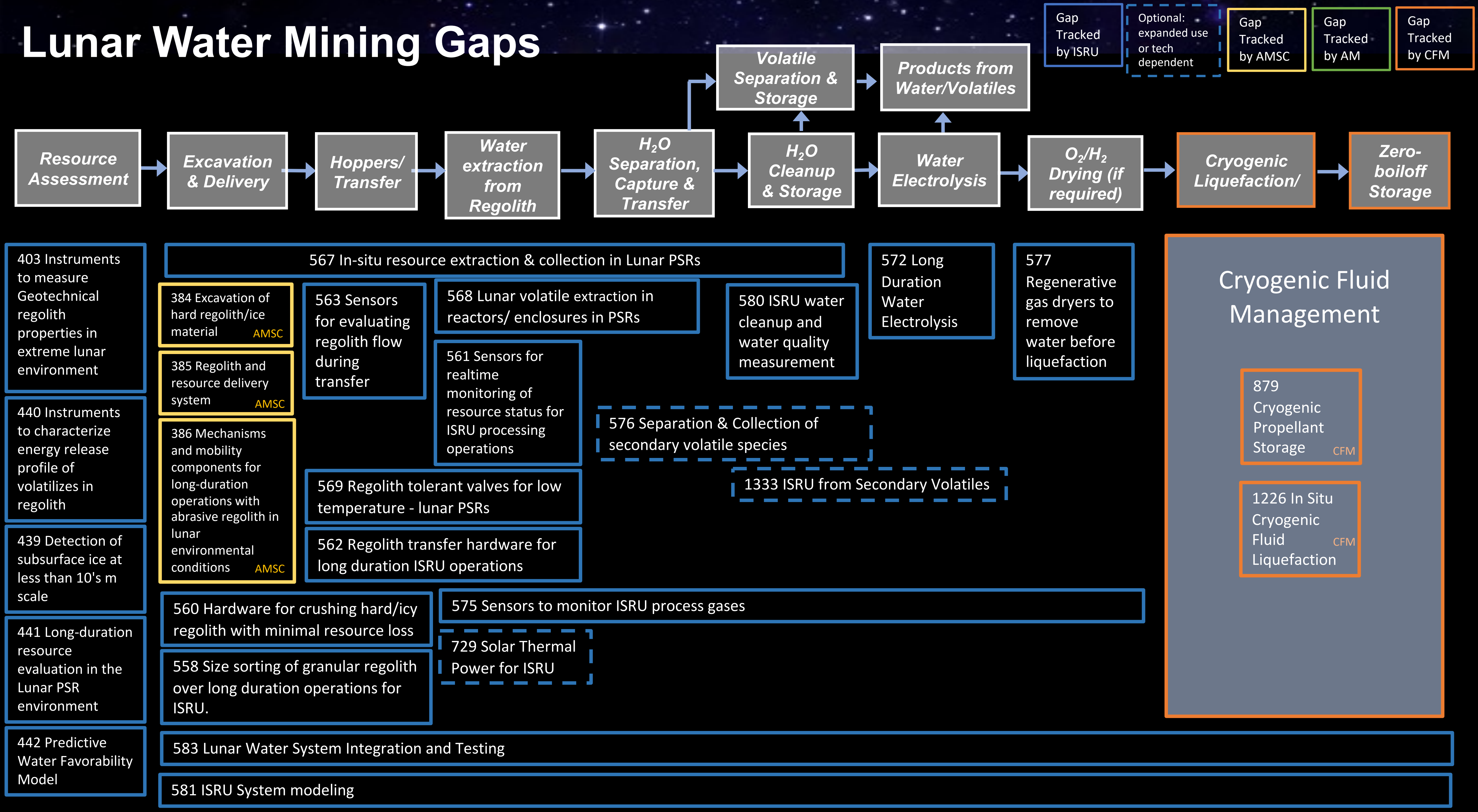

Vibratory Regolith Transfer


Water Capture, Cleanup, & PEM Electrolysis


Large Deployable Solar Concentrators


3D Printing w/ Lunar Concrete

Lunar Water Mining Gaps



Gap Tracked by ISRU

Optional: expanded use or tech dependent

Gap Tracked by AMSC

Gap Tracked by AM

Gap Tracked by CFM

Resource Assessment → **Excavation & Delivery** → **Hoppers/ Transfer** → **Water extraction from Regolith** → **H_2O Separation, Capture & Transfer** → **H_2O Cleanup & Storage** → **Water Electrolysis** → **O_2/H_2 Drying (if required)** → **Cryogenic Liquefaction/** → **Zero-boiloff Storage**

Volatile Separation & Storage → **Products from Water/Volatiles**

403 Instruments to measure Geotechnical regolith properties in extreme lunar environment

440 Instruments to characterize energy release profile of volatilizes in regolith

439 Detection of subsurface ice at less than 10's m scale

441 Long-duration resource evaluation in the Lunar PSR environment

442 Predictive Water Favorability Model

567 In-situ resource extraction & collection in Lunar PSRs

384 Excavation of hard regolith/ice material AMSC

385 Regolith and resource delivery system AMSC

386 Mechanisms and mobility components for long-duration operations with abrasive regolith in lunar environmental conditions AMSC

563 Sensors for evaluating regolith flow during transfer

568 Lunar volatile extraction in reactors/ enclosures in PSRs

561 Sensors for realtime monitoring of resource status for ISRU processing operations

580 ISRU water cleanup and water quality measurement

572 Long Duration Water Electrolysis

577 Regenerative gas dryers to remove water before liquefaction

576 Separation & Collection of secondary volatile species

1333 ISRU from Secondary Volatiles

569 Regolith tolerant valves for low temperature - lunar PSRs

562 Regolith transfer hardware for long duration ISRU operations

560 Hardware for crushing hard/icy regolith with minimal resource loss

558 Size sorting of granular regolith over long duration operations for ISRU.

575 Sensors to monitor ISRU process gases

729 Solar Thermal Power for ISRU

Cryogenic Fluid Management

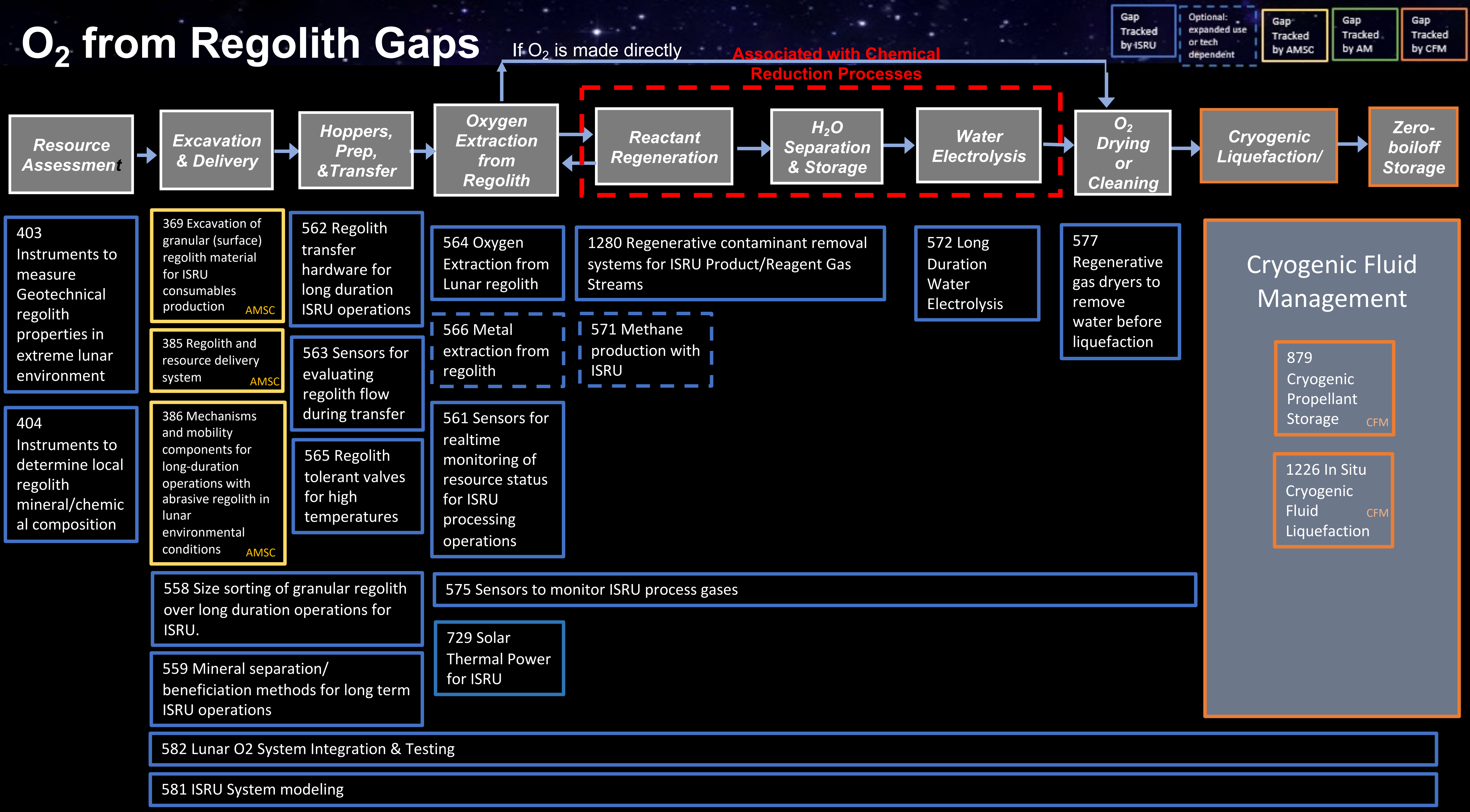
879 Cryogenic Propellant Storage CFM

1226 In Situ Cryogenic Fluid Liquefaction CFM

583 Lunar Water System Integration and Testing

581 ISRU System modeling

O_2 from Regolith Gaps



Gap Tracked by ISRU

Optional: expanded use or tech dependent

Gap Tracked by AMSC

Gap Tracked by AM

Gap Tracked by CFM

If O_2 is made directly

Associated with Chemical Reduction Processes

Resource Assessment → **Excavation & Delivery** → **Hoppers, Prep, &Transfer** → **Oxygen Extraction from Regolith** ⇄ **Reactant Regeneration** → **H_2O Separation & Storage** → **Water Electrolysis** → **O_2 Drying or Cleaning** → **Cryogenic Liquefaction/** → **Zero-boiloff Storage**

403 Instruments to measure Geotechnical regolith properties in extreme lunar environment

404 Instruments to determine local regolith mineral/chemical composition

369 Excavation of granular (surface) regolith material for ISRU consumables production AMSC

385 Regolith and resource delivery system AMSC

386 Mechanisms and mobility components for long-duration operations with abrasive regolith in lunar environmental conditions AMSC

562 Regolith transfer hardware for long duration ISRU operations

563 Sensors for evaluating regolith flow during transfer

565 Regolith tolerant valves for high temperatures

564 Oxygen Extraction from Lunar regolith

566 Metal extraction from regolith

561 Sensors for realtime monitoring of resource status for ISRU processing operations

1280 Regenerative contaminant removal systems for ISRU Product/Reagent Gas Streams

571 Methane production with ISRU

572 Long Duration Water Electrolysis

577 Regenerative gas dryers to remove water before liquefaction

Cryogenic Fluid Management

879 Cryogenic Propellant Storage CFM

1226 In Situ Cryogenic Fluid Liquefaction CFM

558 Size sorting of granular regolith over long duration operations for ISRU.

559 Mineral separation/ beneficiation methods for long term ISRU operations

575 Sensors to monitor ISRU process gases

729 Solar Thermal Power for ISRU

582 Lunar O2 System Integration & Testing

581 ISRU System modeling

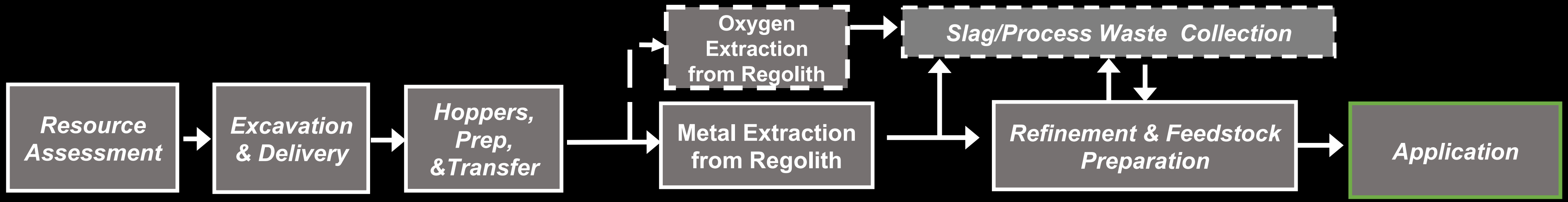
Metal/Silicon Extraction Gaps

Gap Tracked by ISRU

Optional: expanded use or tech dependent

Gap Tracked by AMSC

Gap Tracked by AM



Resource Assessment

Excavation & Delivery

Hoppers, Prep, &Transfer

Oxygen Extraction from Regolith

Metal Extraction from Regolith

Slag/Process Waste Collection

Refinement & Feedstock Preparation

Application

403 Instruments to measure Geotechnical regolith properties in extreme lunar environment

404 Instruments to determine local regolith mineral/chemical composition

369 Excavation of granular (surface) regolith material for ISRU consumables production AMSC

385 Regolith and resource delivery system AMSC

386 Mechanisms and mobility components for long-duration operations with abrasive regolith in lunar environmental conditions AMSC

434 Basic transportation of loose regolith within an AM system for deposition AMSC

562 Regolith transfer hardware for long duration ISRU operations

563 Sensors for evaluating regolith flow during transfer

565 Regolith tolerant valves for high temperatures

558 Size sorting of granular regolith over long duration operations for ISRU.

559 Mineral separation/ beneficiation methods for long term ISRU operations

566 Metal extraction from regolith

561 Sensors for realtime monitoring of resource status for ISRU processing operations

564 Oxygen Extraction from Lunar regolith

575 Sensors to monitor ISRU process gases

729 Solar Thermal Power for ISRU

581 ISRU System modeling

582 Lunar O2 System Integration & Testing

427 ISRU-derived Materials to Usable Construction Feedstock AMSC

432 Extrusion of molten materials (regolith or metal / regolith blend) AMSC

801 Inability to produce manufacturing feedstocks in situ from lunar or Martian materials MANU

Advanced Manufacturing

644 Lunar surface manufacturing and outfitting with metals, polymers, and composites MANU

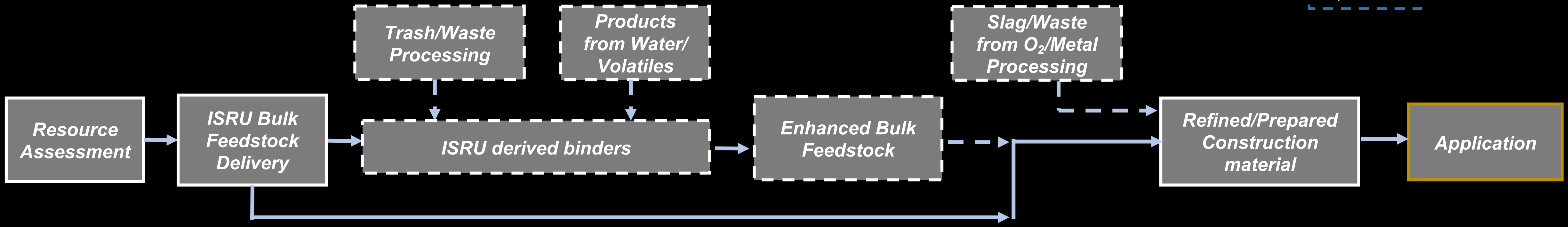
Construction Feedstock Production Gaps

Gap Tracked by ISRU

Optional: expanded use or tech dependent

Gap Tracked by AMSC

Gap Tracked by AM



Resource Assessment

ISRU Bulk Feedstock Delivery

Trash/Waste Processing

Products from Water/ Volatiles

ISRU derived binders

Enhanced Bulk Feedstock

Slag/Waste from O_2/Metal Processing

Refined/Prepared Construction material

Application

403 Instruments to measure Geotechnical regolith properties in extreme lunar environment

404 Instruments to determine local regolith mineral/chemical composition

385 Regolith and resource delivery system AMSC

426 In-situ Analysis of Input Material AMSC

562 Regolith transfer hardware for long duration ISRU operations

558 Size sorting of granular regolith over long duration operations for ISRU.

563 Sensors for evaluating regolith flow during transfer

581 ISRU System modeling

589 ISRU from waste materials

1333 ISRU from Secondary Volatiles

561 Sensors for realtime monitoring of resource status for ISRU processing operations

432 Extrusion of molten materials (regolith or metal / regolith blend) AMSC

667 Extrusion of Polymer/Regolith-based material for in-situ additive construction AMSC

428 Development of ISRU-based 'concrete' reinforcement materials. AMSC

433 Extrusion of cementitious (binder plus regolith as aggregate) materials (Water and Waterless based) AMSC

430 Laser Sintering of Regolith AMSC

431 Microwave Sintering of Regolith AMSC

427 ISRU-derived Materials to Usable Construction Feedstock AMSC

Advanced Materials Structures & Construction

669 Polymer-regolith construction system AMSC

Advanced Manufacturing

644 Lunar surface manufacturing and outfitting with metals, polymers, and composites MANU

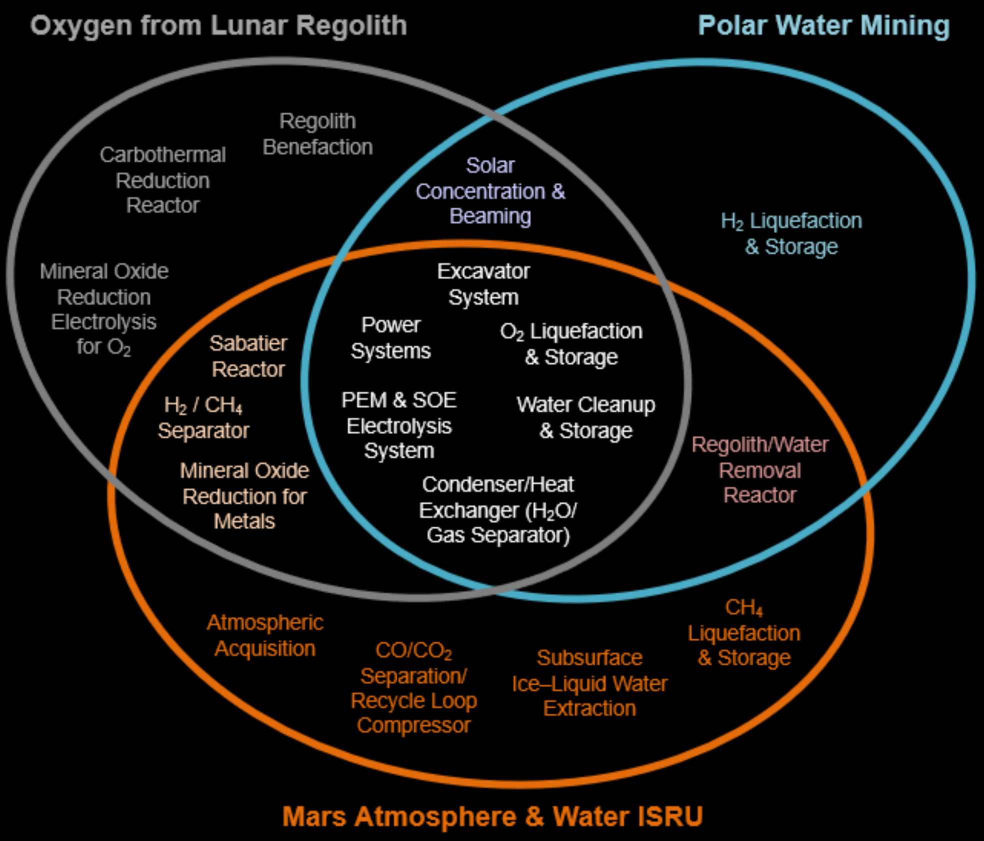
Moon to Mars Forward ISRU

- **Identify, characterize, and quantify environments and resources for Science and ISRU**
  - Quantify concentration and lateral/vertical distribution of resources/water/volatiles at multiple locations to provide geological context for science-focused theories of resource placement and initial mining assessments.
  - Test technologies and processes to reduce risk of future extraction/ mining systems

- **Demonstrate ISRU concepts, technologies, & hardware applicable to Mars**
  - ISRU for propellant production with modular/scalable hardware (both Moon and Mars require similar production rates)
    - Regolith excavation and delivery
    - Water and CO_2 collection, separation, chemical processing, and cleanup technologies
    - Liquefy, store, transfer, and fill ascent vehicle propellant tanks
  - Surface civil engineering and infrastructure emplacement for repeated landing/ascent at same location

- **Use Moon for operational experience and mission validation for Mars**
  - Pre-deployment & remote activation and operation of ISRU assets without crew; especially excavation
  - Making and transferring mission consumables (propellants, life support, power, etc.)
  - Landing crew with 'empty' tanks with ISRU propellants already made and waiting

ISRU Technology Synergy



Oxygen from Lunar Regolith

Polar Water Mining

Carbothermal Reduction Reactor

Regolith Benefaction

Solar Concentration & Beaming

H_2 Liquefaction & Storage

Mineral Oxide Reduction Electrolysis for O_2

Excavator System

Sabatier Reactor

Power Systems

O_2 Liquefaction & Storage

H_2 / CH_4 Separator

PEM & SOE Electrolysis System

Water Cleanup & Storage

Regolith/Water Removal Reactor

Mineral Oxide Reduction for Metals

Condenser/Heat Exchanger (H_2O/ Gas Separator)

Atmospheric Acquisition

CH_4 Liquefaction & Storage

CO/CO_2 Separation/ Recycle Loop Compressor

Subsurface Ice–Liquid Water Extraction

Mars Atmosphere & Water ISRU

Lunar & Mars Production Synergy

Lunar Production Target

10 mt O_2 / yr
or
15 mt H_2O / yr

Lunar ISRU

- Resource acquisition (225 – 1360 kg / day)
- Oxygen production (2.0 kg O_2 / hr)
- Water electrolysis (2.8 kg H_2O / hr)

Mars ISRU

- Resource acquisition (720 – 2660 kg / day)
- Oxygen production (2.2 – 2.7 kg O_2 / hr)
- Water electrolysis (3.0 kg H_2O / hr)

Mars Production Target

23 mt O_2 only
or
28 mt O_2 & 7 mt CH_4
per mission (~26 months)

Will use modularity to ensure applicability of hardware to both Moon and Mars ISRU

Oxygen (O_2) from Mars Atmosphere Gaps

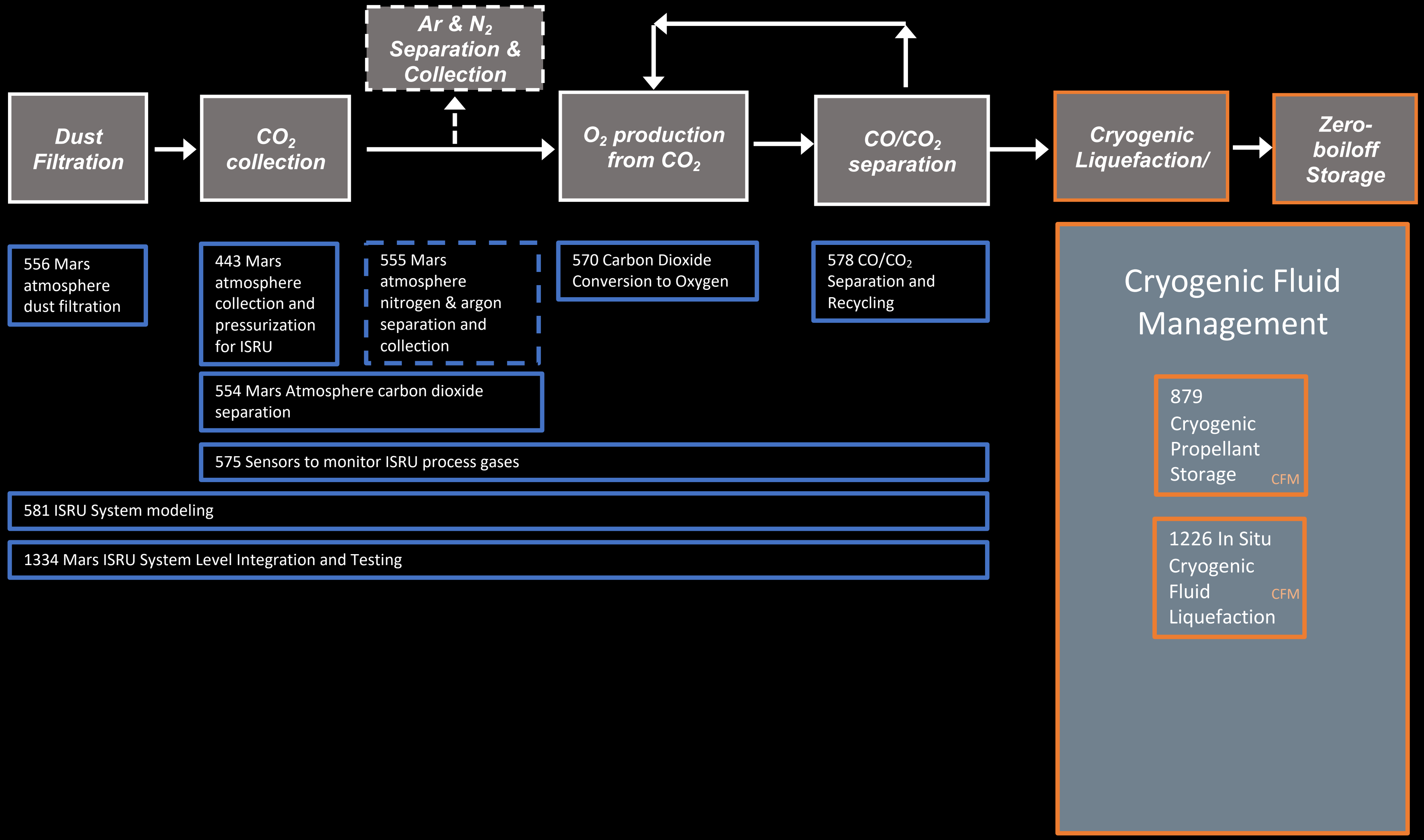
Gap Tracked by ISRU

Optional: expanded use or tech dependent

Gap Tracked by AMSC

Gap Tracked by AM

Gap Tracked by CFM



Dust Filtration → **CO_2 collection** → **O_2 production from CO_2** → **CO/CO_2 separation** → **Cryogenic Liquefaction/** → **Zero-boiloff Storage**

Ar & N_2 Separation & Collection

556 Mars atmosphere dust filtration

443 Mars atmosphere collection and pressurization for ISRU

555 Mars atmosphere nitrogen & argon separation and collection

570 Carbon Dioxide Conversion to Oxygen

578 CO/CO_2 Separation and Recycling

554 Mars Atmosphere carbon dioxide separation

575 Sensors to monitor ISRU process gases

581 ISRU System modeling

1334 Mars ISRU System Level Integration and Testing

Cryogenic Fluid Management

879 Cryogenic Propellant Storage CFM

1226 In Situ Cryogenic Fluid Liquefaction CFM

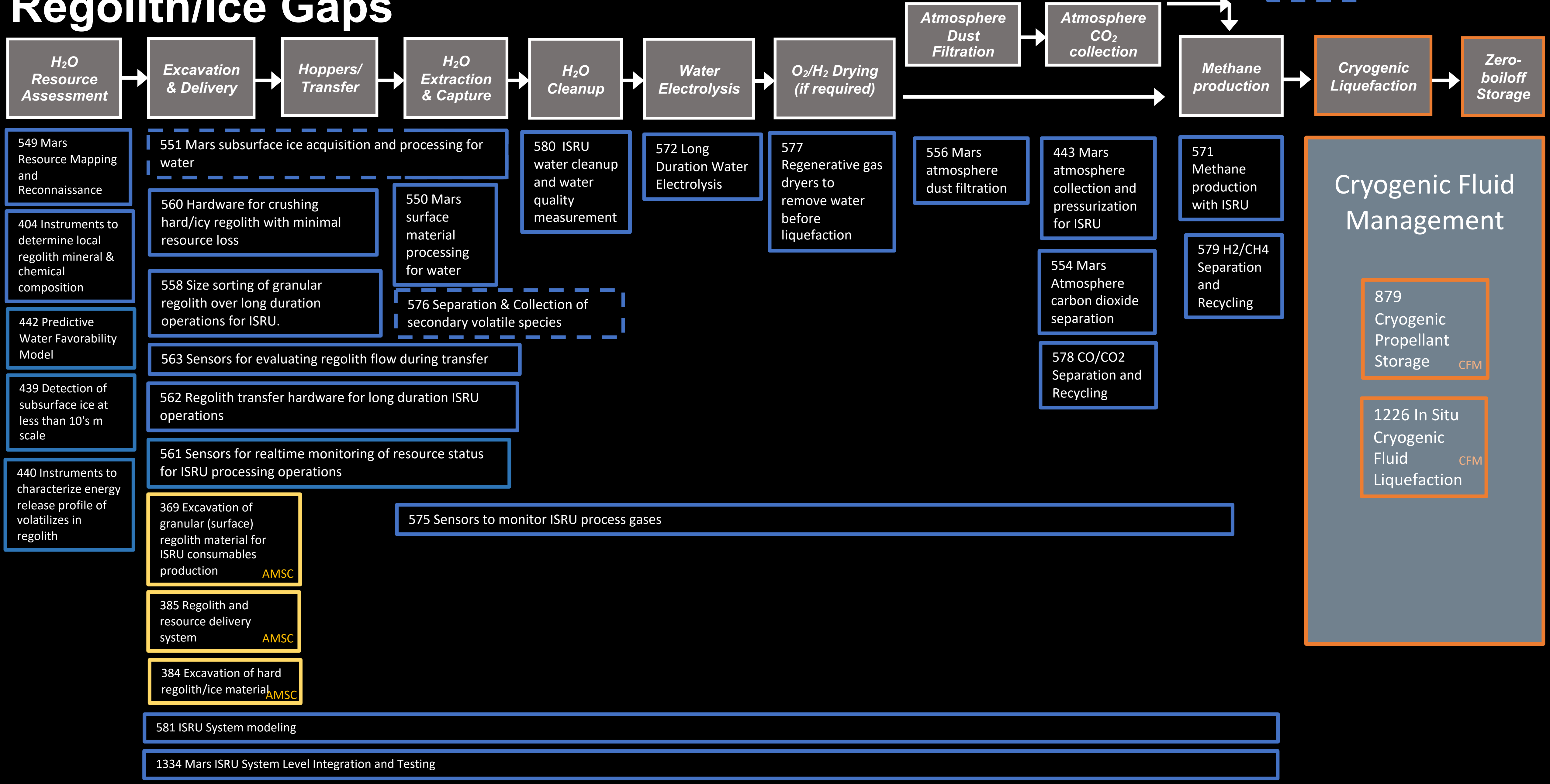
O_2/Fuel from Mars Atmosphere & Water from Regolith/Ice Gaps

Gap Tracked by ISRU

Optional: expanded use or tech dependent

Gap Tracked by AMSC

Gap Tracked by CFM



H_2O Resource Assessment → ***Excavation & Delivery*** → ***Hoppers/ Transfer*** → ***H_2O Extraction & Capture*** → ***H_2O Cleanup*** → ***Water Electrolysis*** → ***O_2/H_2 Drying (if required)*** → ***Methane production*** → ***Cryogenic Liquefaction*** → ***Zero-boiloff Storage***

Atmosphere Dust Filtration → ***Atmosphere CO_2 collection*** → ***Methane production***

H_2O Resource Assessment:
- 549 Mars Resource Mapping and Reconnaissance
- 404 Instruments to determine local regolith mineral & chemical composition
- 442 Predictive Water Favorability Model
- 439 Detection of subsurface ice at less than 10's m scale
- 440 Instruments to characterize energy release profile of volatilizes in regolith

Excavation & Delivery / Hoppers/Transfer / H_2O Extraction & Capture:
- 551 Mars subsurface ice acquisition and processing for water
- 560 Hardware for crushing hard/icy regolith with minimal resource loss
- 550 Mars surface material processing for water
- 558 Size sorting of granular regolith over long duration operations for ISRU.
- 576 Separation & Collection of secondary volatile species
- 563 Sensors for evaluating regolith flow during transfer
- 562 Regolith transfer hardware for long duration ISRU operations
- 561 Sensors for realtime monitoring of resource status for ISRU processing operations
- 369 Excavation of granular (surface) regolith material for ISRU consumables production AMSC
- 385 Regolith and resource delivery system AMSC
- 384 Excavation of hard regolith/ice material AMSC

H_2O Cleanup:
- 580 ISRU water cleanup and water quality measurement

Water Electrolysis:
- 572 Long Duration Water Electrolysis

O_2/H_2 Drying (if required):
- 577 Regenerative gas dryers to remove water before liquefaction

Atmosphere Dust Filtration:
- 556 Mars atmosphere dust filtration

Atmosphere CO_2 collection:
- 443 Mars atmosphere collection and pressurization for ISRU
- 554 Mars Atmosphere carbon dioxide separation
- 578 CO/CO2 Separation and Recycling

Methane production:
- 571 Methane production with ISRU
- 579 H2/CH4 Separation and Recycling

Cryogenic Liquefaction / Zero-boiloff Storage:

Cryogenic Fluid Management
- 879 Cryogenic Propellant Storage CFM
- 1226 In Situ Cryogenic Fluid Liquefaction CFM

575 Sensors to monitor ISRU process gases

581 ISRU System modeling

1334 Mars ISRU System Level Integration and Testing

ISRU Commodity Production Investment Status (1 of 2)

Green = Significant Funded Activities
Yellow = Partially Covered; More Required
Red = Limited/No Funded Activities

- **Develop Critical Technologies for Lunar Oxygen Extraction**
  - ☑ 6 different O_2 extraction technologies in development – 2 showing significant promise
  - ☑ 3 different water electrolysis (PEM, SOE, Alkaline) approaches (with Life Support and Regenerative Power)
  - ☐ Interface and internal technologies/functional areas require further investment
- **Develop Critical Technologies for Lunar Resource Assessment and Water Extraction**
  - ☑ Significant number of SMD and STMD instrument technologies for resource assessment down to 1 m.; University/Public Challenges
  - ☒ Need to consider technologies for deeper >3 m assessment for water/volatiles based on some water deposit theories
  - ☐ 3 different water mining development approaches – limited test success and cancellation
  - ☑ 3 different water electrolysis approaches (with Life Support and Regenerative Power)
  - ☐ Interface and internal technologies/functional areas require further investment
  - ☒ No dedicated robotic polar water/volatile resource assessment surface missions beyond VIPER currently in planning
  - ☒ No dedicated funded effort to develop resource maps for site selection
- **Develop Critical Technologies for Manufacturing and Construction Feedstocks/Commodities**
  - ☐ Technologies for raw metal/alloy extraction in work as part of O_2 extraction; Open solicitations and BIGIdeas Challenge
  - ☐ Technologies for regolith size sorting, mineral beneficiation, and regolith manipulation in work
  - ☐ Development and evaluation feedstocks to support manufacturing and construction techniques
  - ☒ Limited plastic/binder production from in situ resources; terrestrial and synthetic biology technologies in work for bio-plastic
- **Evaluate and Develop Integrated Systems for Extended Ground Testing; Tie to Other Discipline Plans**
  - ☑ NASA and APL performed/performing ISRU system evaluations
  - ☐ Dedicated modeling, evaluation criteria, and Figures of Merit (FOMs) established
  - ☒ Approval/funding for integration and testing of lunar technologies into end-to-end systems required to support ISRU Pilot plant development
  - ☒ Approval/funding for of human-mission scale Mars ISRU technologies into end-to-end system required to support MI-4
  - ☑ Facilities and simulants to support lunar environmental testing with regolith simulants – Large chamber capability still an issue
  - ☐ Facilities and approach for extended mission analog operation and evaluation ground testing

ISRU Commodity Production Investment Status (2 of 2)

- **Develop/Fly Resource Assessment & ISRU Demonstrations Missions leading to Pilot Plant operations by 2030**
  - ☑ Orbital missions, PRIME-1, & VIPER funded and under development for launch
  - ☐ Lunar Trailblazer launch date and mission data later than desired. Actual spacecraft ready for launch in 2022
  - ☒ No clear plan for polar water/volatile resource assessment leading to Base Camp site selection – predicated on success of VIPER
  - ☐ At least one demonstration planned for each ISRU commodity path

- **Involve Industry/Academia with Goal of Commercial Space Operations at Scale**
  - ☑ NIACs, SBIRs, BAAs, ACOs, & TPs led by industry underway for ISRU
  - ☑ STTRs, NIACs, LuSTR, NSTRF, ESI/ECF led by Academia underway for ISRU
  - ☑ Lunar Surface Innovation Consortium – ISRU Focus Group underway and active; Supply/Demand Workshop
  - ☐ Center for the Utilization of Biological Engineering in Space (CUBES) – Completed and new funding being sought
  - ☑ NASA prize competitions and university challenges: BIG Idea, Moon-Mars Ice Prospecting, Break the Ice Lunar, Lunabotics, CO_2 Conversion Challenge, Space Robotics Challenge
  - ☐ Selection/Competition strategy for ISRU demonstrations and Pilot Plant in work for industry involvement and commercialization

Green = Significant Funded Activities
Yellow = Partially Covered; More Required
Red = Limited/No Funded Activities

ISRU EFP - Next Step Priorities

- **Initiate solicitations with Industry to progress ISRU technologies to Demonstration & Pilot-scale flights**
  - Pursue oxygen and metal extraction demonstrations; delay water mining demonstration until better knowledge is obtained
  - Provide feedstock technologies and capabilities to support construction demonstrations
  - Identify and pursue new options/approaches for utilizing significant mission mass/frequency capabilities with HLS providers
- **Initiate Internal and Industry-led System-level integration of ISRU and infrastructure capabilities for Pilot/Full-Scale**
  - Expand ISRU system engineering, modeling, integration, and testing to enable technology and system selections
  - Begin combining power, excavation, ISRU, storage & transfer, comm/nav, autonomy/avionics, maintenance/crew.
- **Expand Development of Metal/Aluminum Extraction & other Feedstock for Manufacturing & Construction**
  - Continue and expand work on combined oxygen and metal extraction technologies;
  - Initiate work focused on metal extraction and processes leading to more pure/refined metals
  - Consider longer-term interests in mare regolith minerals and resources: Ilmenite, Pyroclastic glasses, KREEP, Solar wind implanted volatiles
  - Continue and expand construction feedstock/commodity development with in-space manufacturing and construction
  - Evaluate synthetic biology technologies for bio-mining, bio-plastic, and some commodity feedstocks
- **Initiate Mars ISRU Technology and System Risk Reduction Development and Testing for M2M Objective MI-4**
  - Perform system Integration of existing/near-existing Mars human mission scale hardware and perform testing to reduce the risk for architecture insertion
  - Coordinate evaluation of Mars resources and mission insertion with SMD and ESDMD/SOMD
- **Advance Lunar Polar Water/Volatile Prospecting/Mapping and Technology Development**
  - Coordinate Polar Resource Assessment and Mapping (M2M AS-3) with SMD, ESDMD/SOMD, and industry for mining site selection
  - Continue evaluating/developing water mining technologies in parallel with polar resource assessment
- **Initiate Closer-Ties and Coordination with Life Support Systems**
  - Develop needs/objectives, and perform technology assessment/development for nutrients/food/agriculture feedstocks for sustained presence
  - Work with life support on oxygen and water cleanup technologies and requirements
  - Work with life support on conversion of wastes into usable products; eliminate trash dumping

Backup: Further Information on ISRU Gaps

ISRU Gap List (1 of 2)

Capability	Gap Number	Gap Name	Mars	Moon	Water	O2R	Metal	Raw Regolith	Atm	Other
ISRU	403	Instruments to measure Geotechnical regolith properties in extreme lunar environment		X	■	■	■	■		■
ISRU	404	Instruments to determine local regolith mineral/chemical composition	v	X		■	■	v		■
ISRU	439	Detection of subsurface ice at less than 10's m scale	X	X	■					v
ISRU	440	Instruments to characterize energy release profile of volatilizes in regolith	X	X	■					■
ISRU	441	Long-duration resource evaluation in the Lunar PSR environment		X	■					■
ISRU	442	Predictive Water Favorability Model	X	X	■					
ISRU	443	Mars atmosphere collection and pressurization for ISRU	X						■	
ISRU	549	Mars Resource Mapping and Reconnaissance	X		■					
ISRU	550	Mars surface material processing for water	X		■					
ISRU	551	Mars subsurface ice acquisition and processing for water	X		■					
ISRU	554	Mars atmosphere carbon dioxide separation	X		v				■	
ISRU	555	Mars atmosphere nitrogen/argon separation and collection	X		v				■	
ISRU	556	Mars atmosphere dust filtration	X		v				■	
ISRU	558	Size sorting of granular ~~lunar~~ regolith over long duration operations for ISRU.	X	X	■	■	■	■		■
ISRU	559	Mineral separation/beneficiation methods for long term ISRU operations	X	X		■	■			v
ISRU	560	Hardware for crushing hard/icy regolith with minimal resource loss	X	X	■					
ISRU	561	Sensors for realtime monitoring of resource status for ISRU processing operations	X	X	■	■	■	■		■
ISRU	562	Regolith transfer hardware for long duration ISRU operations	X	X	■	■	■	■		■
ISRU	563	Sensors for evaluating regolith flow during transfer	X	X	■	■	■	■		■
ISRU	564	Oxygen Extraction from Lunar regolith		X		■	v			
ISRU	565	Regolith tolerant valves for high temperatures	v	X		■	■			v
ISRU	566	Metal extraction from regolith		X		v	■			
ISRU	567	In-situ resource extraction & collection in Lunar PSRs		X	■					■
ISRU	568	Lunar volatile extraction in reactors/enclosures in PSRs		X	■					■
ISRU	569	Regolith tolerant valves for low temperature - lunar PSRs		X	■					■
ISRU	570	Carbon Dioxide Conversion to Oxygen	X						■	
ISRU	571	Methane production with ISRU	X	v	■	v			■	
ISRU	572	Long Duration Water Electrolysis	X	X	■	v				v
ISRU	575	Sensors to monitor ISRU process gases	X	X	■	■	■		■	■
ISRU	576	Separation & Collection of secondary volatile species	X	X	v					■
ISRU	577	Regenerative gas dryers to remove water before liquefaction	X	X	■	■				

CONTINUED on NEXT PAGE.....

ISRU Gap List (2 of 2)

Capability	Gap Number	Gap Name	Mars	Moon	Water	O2R	Metal	Raw Regolith	Atm	Other
CONTINUED FROM PREVIOUS PAGE										
ISRU	578	CO/CO2 Separation and Recycling	X						■	
ISRU	579	H2/CH4 Separation and Recycling	X	v	■				■	
ISRU	580	ISRU water cleanup and water quality measurement	X	X	■					v
ISRU	581	ISRU System modeling	X	X	■	■	■	■	■	■
ISRU	582	Lunar O2 System Integration & Testing		X		■	v			
ISRU	583	Lunar Water System Integration and Testing		X	■					v
ISRU	589	ISRU from waste materials and plastics	X	X						■
ISRU	1280	Regenerative contaminant removal systems for ISRU Product/Reagent Gas Streams	v	X		■	■		v	
ISRU	776	Lunar Resource Mapping and Reconnaissance		X	■	v	v			v
ISRU	836	Lunar Dirty Thermal Vacuum Large Test chambers		X	■	■	■	■	■	■
ISRU	862	Mars Dirty Vacuum Large Test chambers	X		■			■		■
ISRU	1333	ISRU from Secondary Volatiles	X	X	■					v
ISRU	1334	Mars ISRU System Level Integration and Testing	X		■				■	
ISRU	729	Solar Thermal Power for ISRU		X	v	■	■			v