EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

In Situ Resource Utilization (ISRU) – Update on Strategy, Scope, Plans, and Priorities

Presentation to Space Resources Roundtable
Golden, CO

June 6, 2023

Gerald (Jerry) Sanders | ISRU System Capability Lead – STMD | gerald.b.sanders@nasa.gov
Julie Kleinhenz | ISRU System Capability Deputy – STMD | julie.e.kleinhenz@nasa.gov

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

Moon to Mars (M2M) Blueprint Objectives and ISRU

- NASA Moon to Mars (M2M) Blueprint Objectives officially released in Sept. 2022 at IAC; Updated 4/2023
- A significant number of objectives align with ISRU in three general areas (Resource Assessment, ISRU and Usage, and Responsible ISRU)
- A significant number of Recuring Tenets are achieved with ISRU development and implementation
- ➢ **Current Artemis Plan is focused on Human Lunar Return and Foundational Lunar Exploration phases**

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] ⬆	Demonstrate **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
LI-8[L]	**Develop** environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.
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

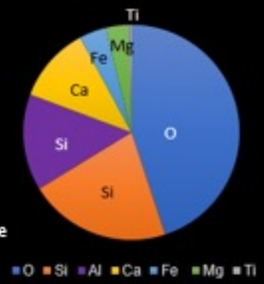
- (green) = Science: Lunar/Planetary Science (LPS), Science-Enabling (SE), Applied Science (AS)
- (purple) = Infrastructure: Lunar Infrastructure (LI), Mars Infrastructure (MI)
- (blue) = Transportation and Habitation (TH)
- (red) = Operations (OP)
- (peach) = Recuring Tenets (RT)

⬆ = Key ISRU M2M Objectives

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

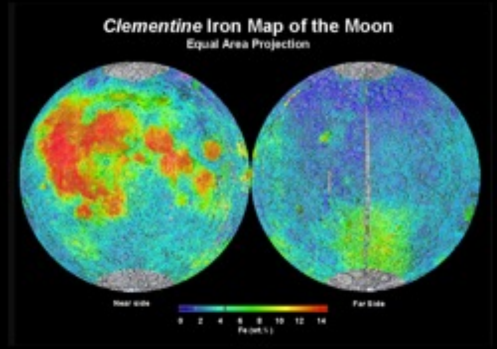
- ISRU starts with the easiest resources to mine, requiring the minimum infrastructure, and providing immediate local usage
- The initial focus is on the lunar South Pole region (highland regolith and water/volatiles in shadowed regions)
  – ISRU will evolve to other locations, more specific minerals,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

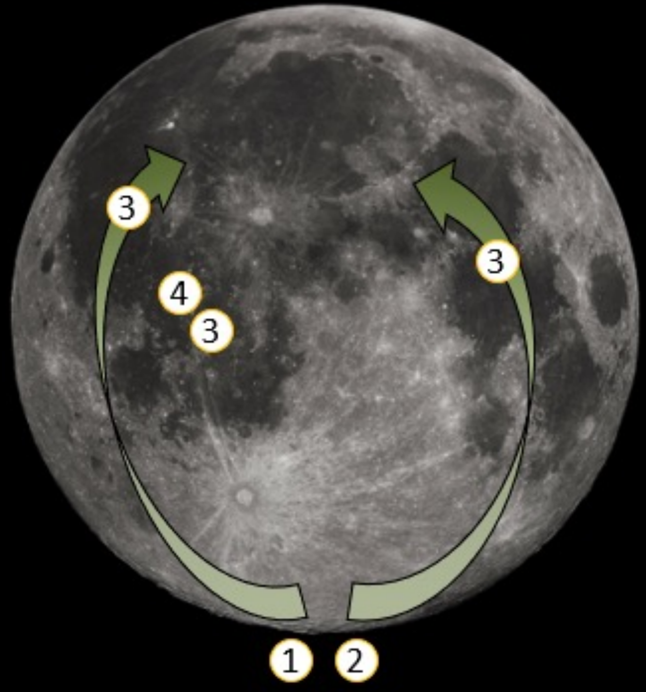
1. Polar Highland Regolith
(Oxygen, Aluminum, Silicon)



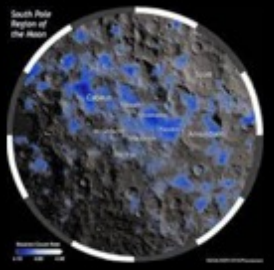
from Planetary and Space Science, Vol. 74,

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





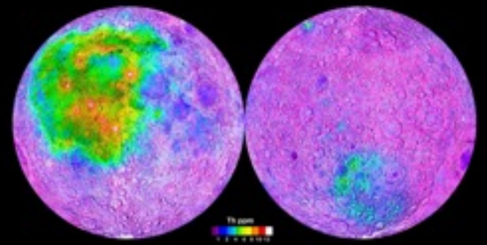
2. Polar Water/Volatiles



LCROSS Impact Volatiles	Concentration (%wt)
H_2O	5.5
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



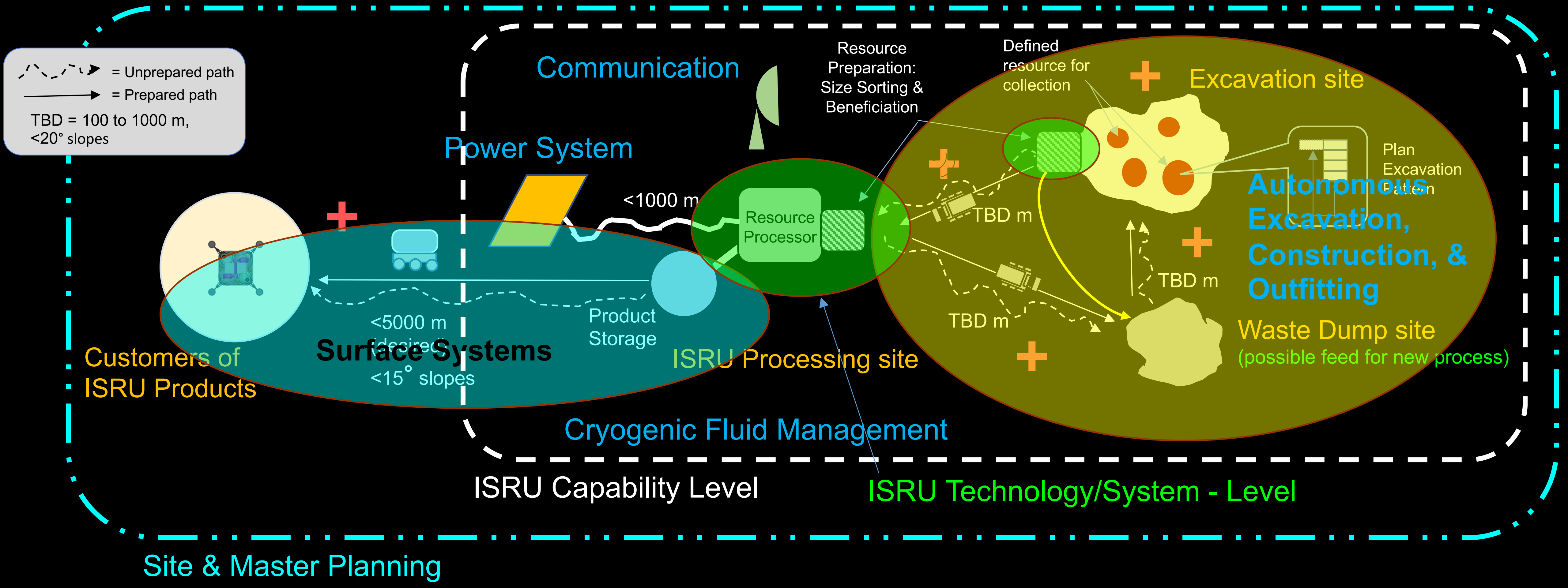
Indication of where KREEP is
(Procellerum KREEP Terrane)

Commodities

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

Lunar ISRU System and Concept of Operations

NASA Discipline Coordination



Two levels of Development, Integration, and Testing

- ISRU Technology and System level development and testing (internal to ISRU domain)
- ISRU Capability level development and testing (coordinate across domains)

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 inside and outside of NASA 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
    - NASA/Government provide to industry key and enabling 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.

Emphasize Industry Involvement

Mining Economics and Mining Phases*

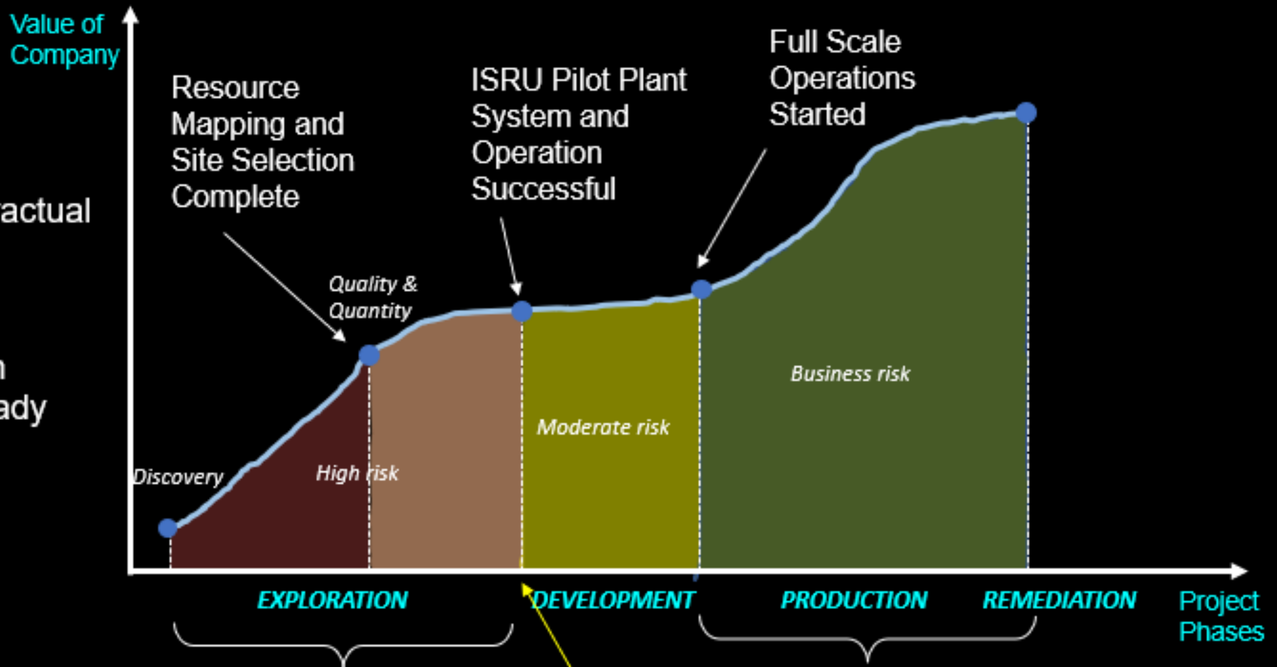
- Define Initial and Long-term Customer Needs and ISRU-derived Products
- Advance ISRU Technologies/Systems (thru solicitations, Public - Private Partnerships, Challenges)
- Focus NASA Work to Reduce Risk and Promote Investment (fundamental research, technology development, facilities, etc.)
  - Foster advancement of circular-economy and 'responsible' space mining practices
- Promote Industry-led development thru End-to-End Production of Commodities
  - Lower barriers of entry and help close the business case

Exploration Phase
- Reserve Definition
- Mining and Recovering Technology Readiness

Development Phase: Feasibility study, contractual and legal aspects, and financing

Production
- Build-up Phase: Startup and initial production
- Plateau Phase: Production rate remains steady
- Decline Phase: Reserves begin to dwindle

Remediation
- Shutdown/removal of mining equipment
- Mine site reclamation



*Government support in **Exploration Phase** may be key to lunar commercial success*

Negative cash flow due to resource assessment and technology development and testing

Positive cash flow due to production and selling of product

Investment risk significantly reduced after successful Pilot Plant demonstration

*Sommariva, A. et al, "The Economics of Moon Mining', International Academy of Astronautics, Torino, Italy, June 17-19, 2019

SPACE TECHNOLOGY PORTFOLIO

ISRU-related activities involved in almost all of them

EARLY STAGE INNOVATION AND PARTNERSHIPS

- Early Stage Innovation
  - Space Tech Research Grants
  - Center Innovation Fund CIF)
  - Early Career Initiative (ECI)
  - Prizes, Challenges & Crowdsourcing
  - NASA Innovation Advanced Concepts
  - Lunar Surface Technology Research (LuSTR)
- Technology Transfer

SBIR/STTR PROGRAMS

- Small Business Innovation Research
  - SBIR Phase I/II/IIe/III
  - SBIR Ignite
  - SBIR Sequential/CCRPP
- Small Business Technology Transfer

TECHNOLOGY MATURATION

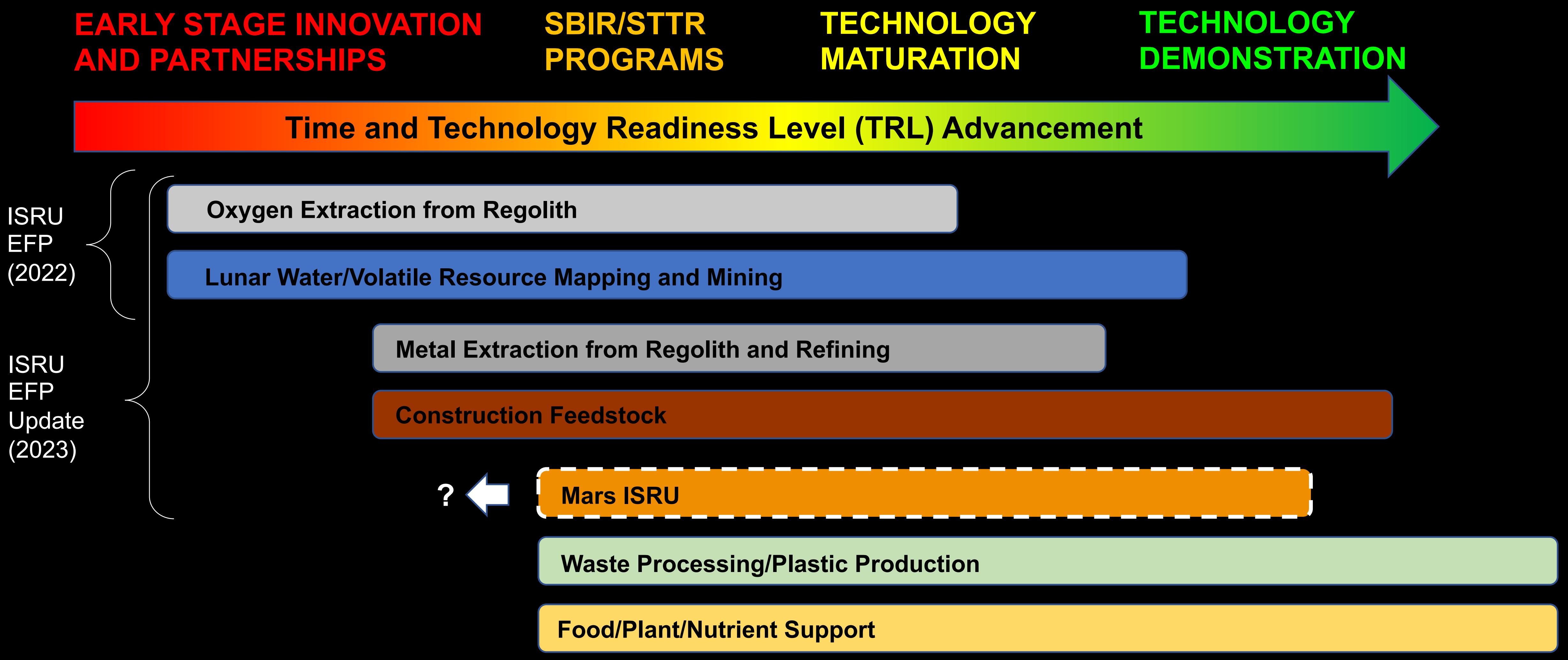
- Game Changing Development
- Lunar Surface Innovation Initiative
- Announcement of Collaboration Opportunity
- Tipping Point

TECHNOLOGY DEMONSTRATION

- Technology Demonstration Missions
- Small Spacecraft Technology
- Flight Opportunities

NASA utilizes a broad portfolio of programs for solicitations, partnerships, and competitions for internal and external development efforts across the TRL spectrum.

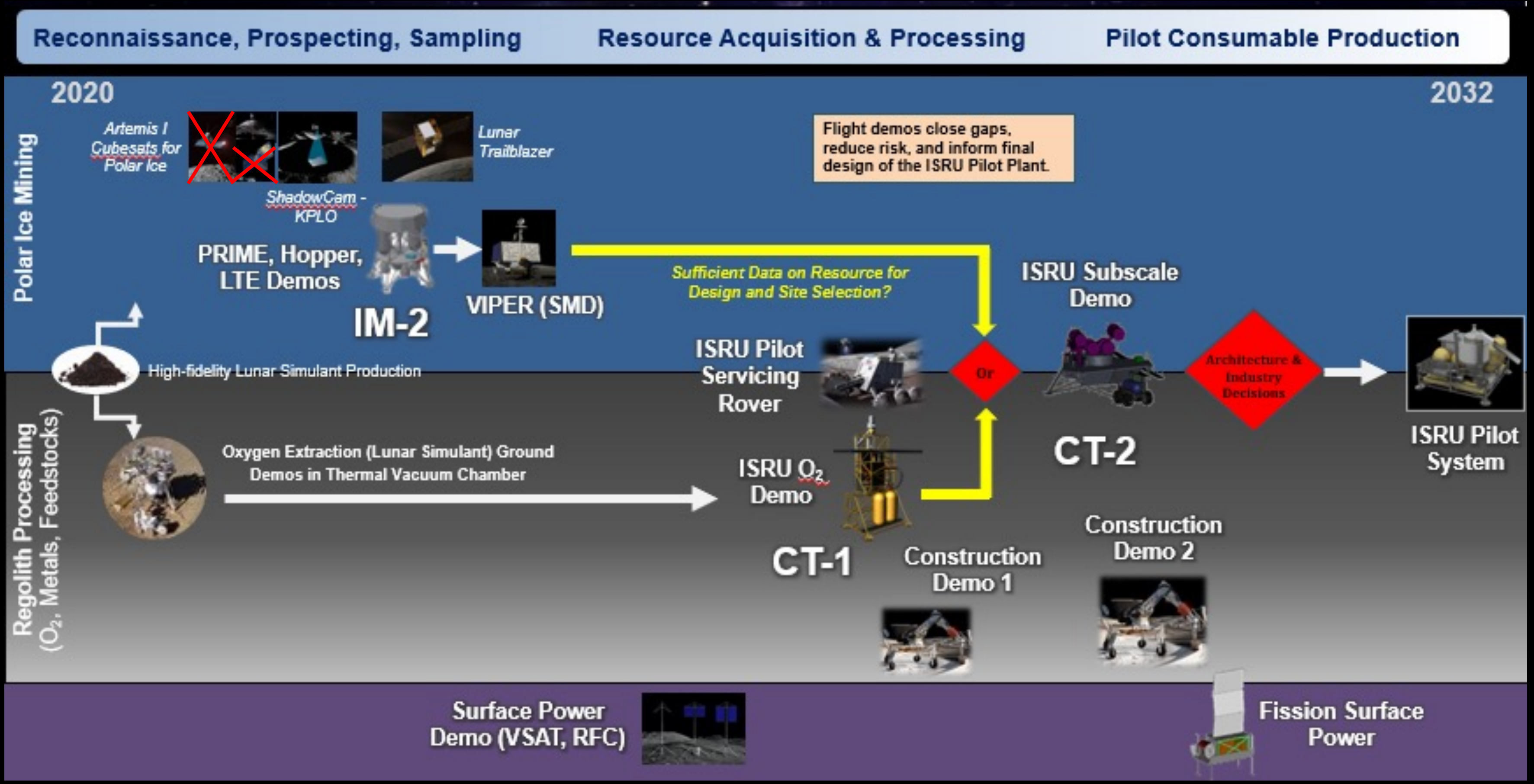
Multiple Areas of ISRU under Development in Phases



- Utilize STMD solicitations and internal work to progress ISRU work areas as TRL progresses
- Initial Focus was on Oxygen Extraction and Water Mining.
  - Now that they have progressed, earlier TRL solicitations moved to next phase of work (Metals and Construction Feedstock) and evaluate specific gaps or next gen high risk/high payoff concepts

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

LI-7[L]	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
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.

Beyond 2032 Not Defined

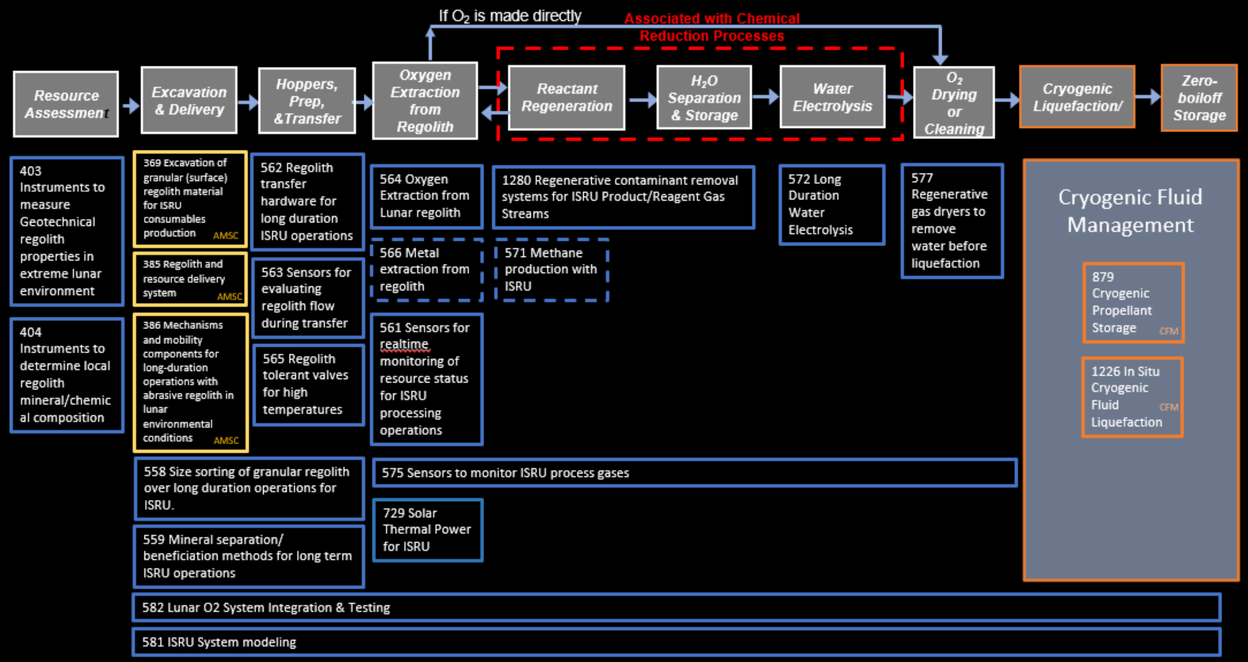
Requires transition and 'Pull' from STMD to ESDMD and Industry

- 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

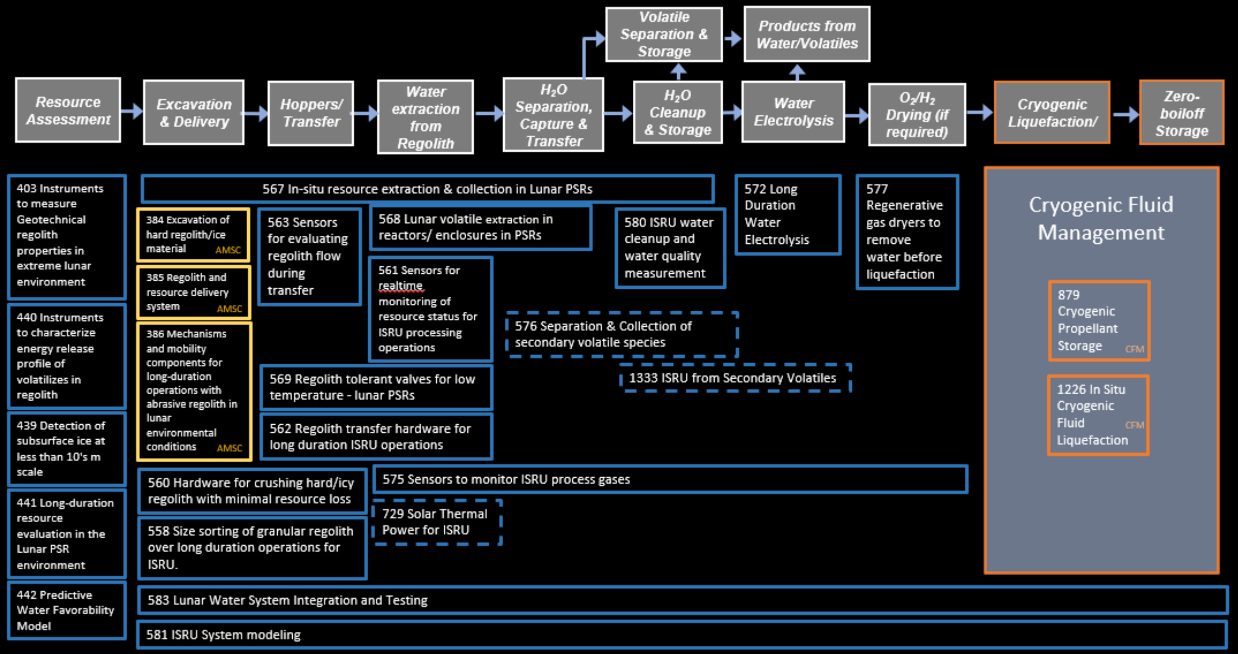
ISRU Lunar Gaps (1 of 2)

Gap Tracked by ISRU | Optional: expanded use or tech dependent | Gap Tracked by AMSC | Gap Tracked by AM | Gap Tracked by CFM

Oxygen Extraction from Regolith



Polar Water/Ice Mining

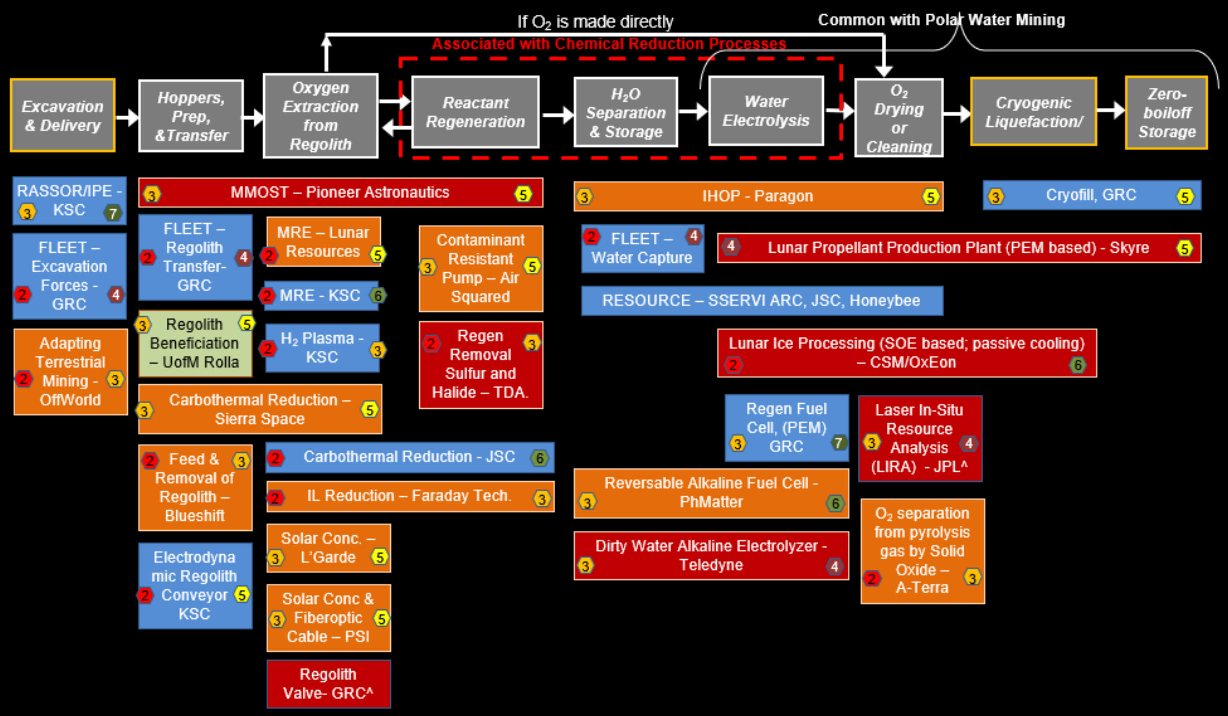


- **Gaps were written in three major areas of ISRU:**
  1) **Destination Reconnaissance & Resource Assessment**
  2) **Resource Acquisition, Isolation, & Preparation**
  3) **Resource Processing (sub-divided further)**
     - **Mission Consumables (Oxygen, Water, Fuels)**
     - **Feedstocks for Construction and Manufacturing**
- **Gaps were mapped to six major ISRU 'Systems'**
  – **2 shown**

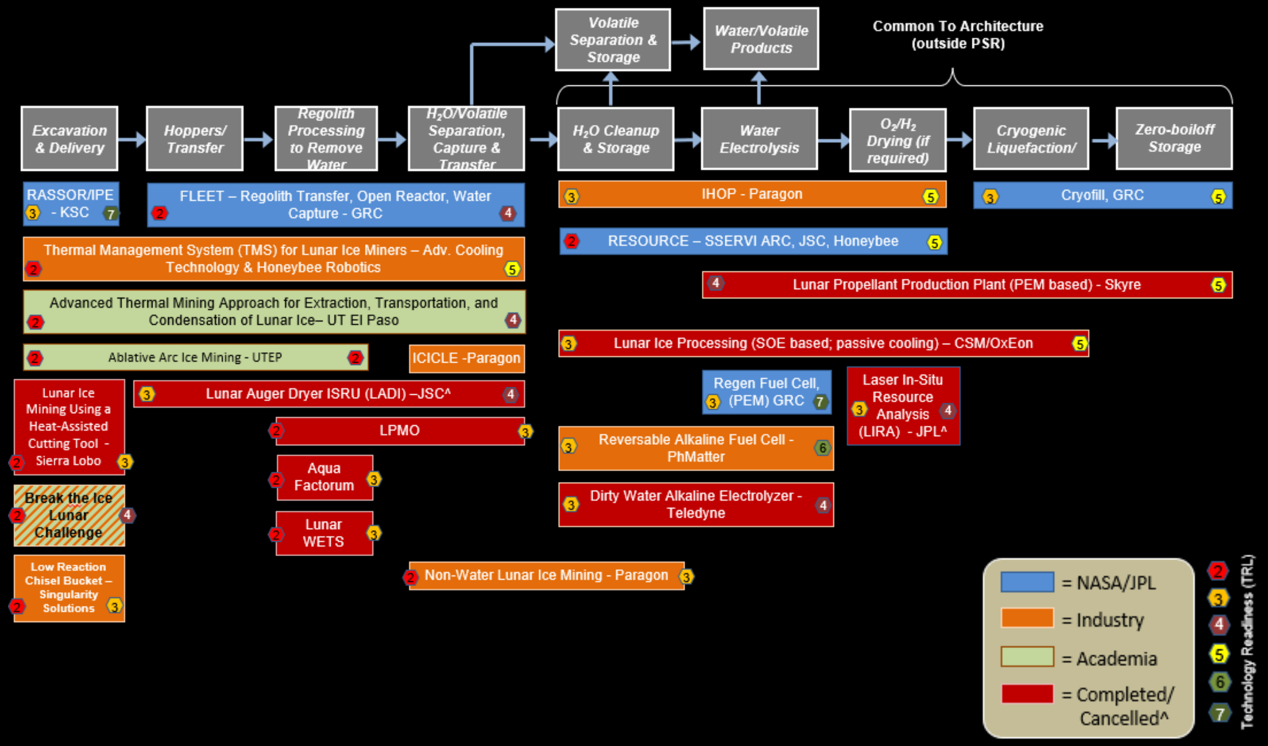
- **Gaps were coordinated with other disciplines involved in ISRU end-to-end systems** (Excavation, CFM, Manufacturing)
- **Gaps were coordinated with other disciplines needed to enable ISRU operations beyond those listed in the charts** (ex. Power)

NASA / Industry Expertise & On-going Work – By ISRU Focus

Oxygen Extraction from Regolith



Polar Water/Ice Mining

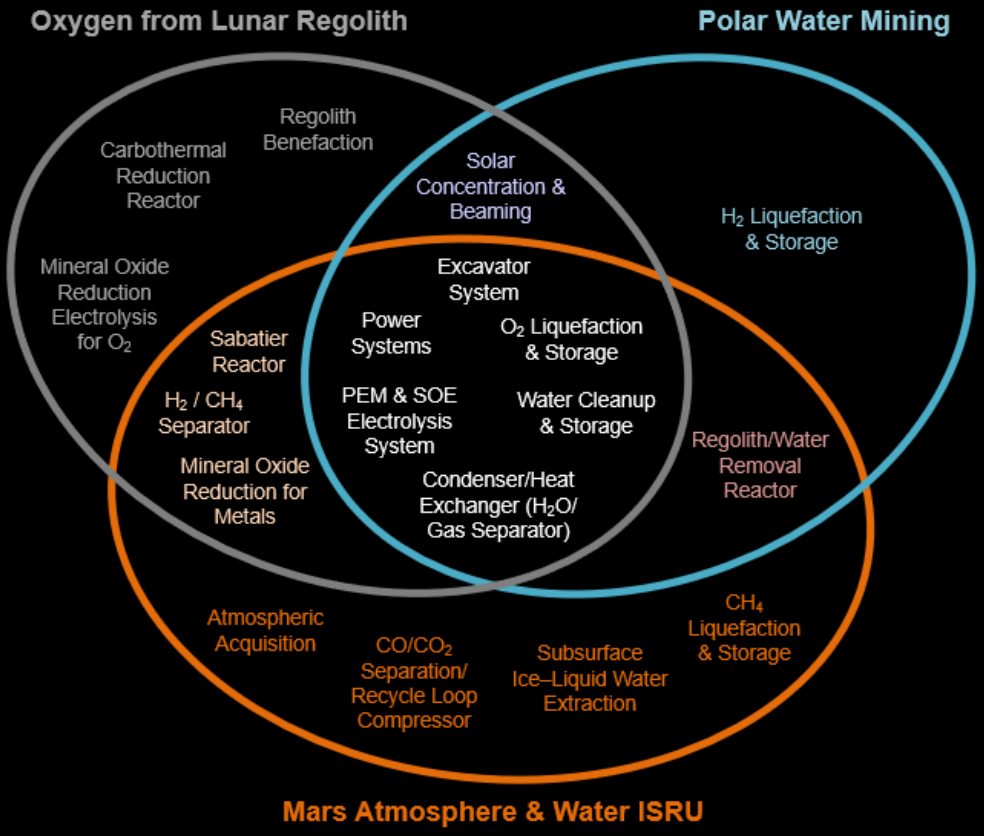


- The bulk of ISRU research and technology development is performed by Industry and academia
- Polar water mining technology work has been either cancelled, low TRL, or completed (under-performed)
- No end-to-end Lunar or Mars ISRU system integration and testing currently funded at this time

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



Lunar & Mars Production Synergy

Lunar Production Target	Lunar ISRU	Mars ISRU	Mars Production Target
10 mt O_2 / yr or 15 mt H_2O / yr	• Resource acquisition (225 – 1360 kg / day) • Oxygen production (2.0 kg O_2 / hr) • Water electrolysis (2.8 kg H_2O / hr)	• Resource acquisition (720 – 2660 kg / day) • Oxygen production (2.2 – 2.7 kg O_2 / hr) • Water electrolysis (3.0 kg H_2O / hr)	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

ISRU Commodity Production Investment Status (1 of 2)

- **Develop Critical Technologies for Lunar Oxygen Extraction**
  - ☑ 6 different O_2 extraction technologies in development – 2 showing significant promise
  - ☑ 3 different water electrolysis approaches (with Life Support and Regenerative Power)
  - ❑ Interface and internal technologies/functional areas require further investment

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

- **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 moved forward
  - ☒ 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

The Space Perspective: a Long-range View

- ISRU can reduce mission and architecture mass and costs
  - Allows us to use fewer launches to get supplies to our destination – propellant, consumables, construction materials, etc.
- ISRU can increase safety for crew and enhance mission capabilities, allowing us to explore farther from Earth with more independence.
- Learning to use space resources can help us on Earth
- Planetary preservation is important in responsibly using space resources.

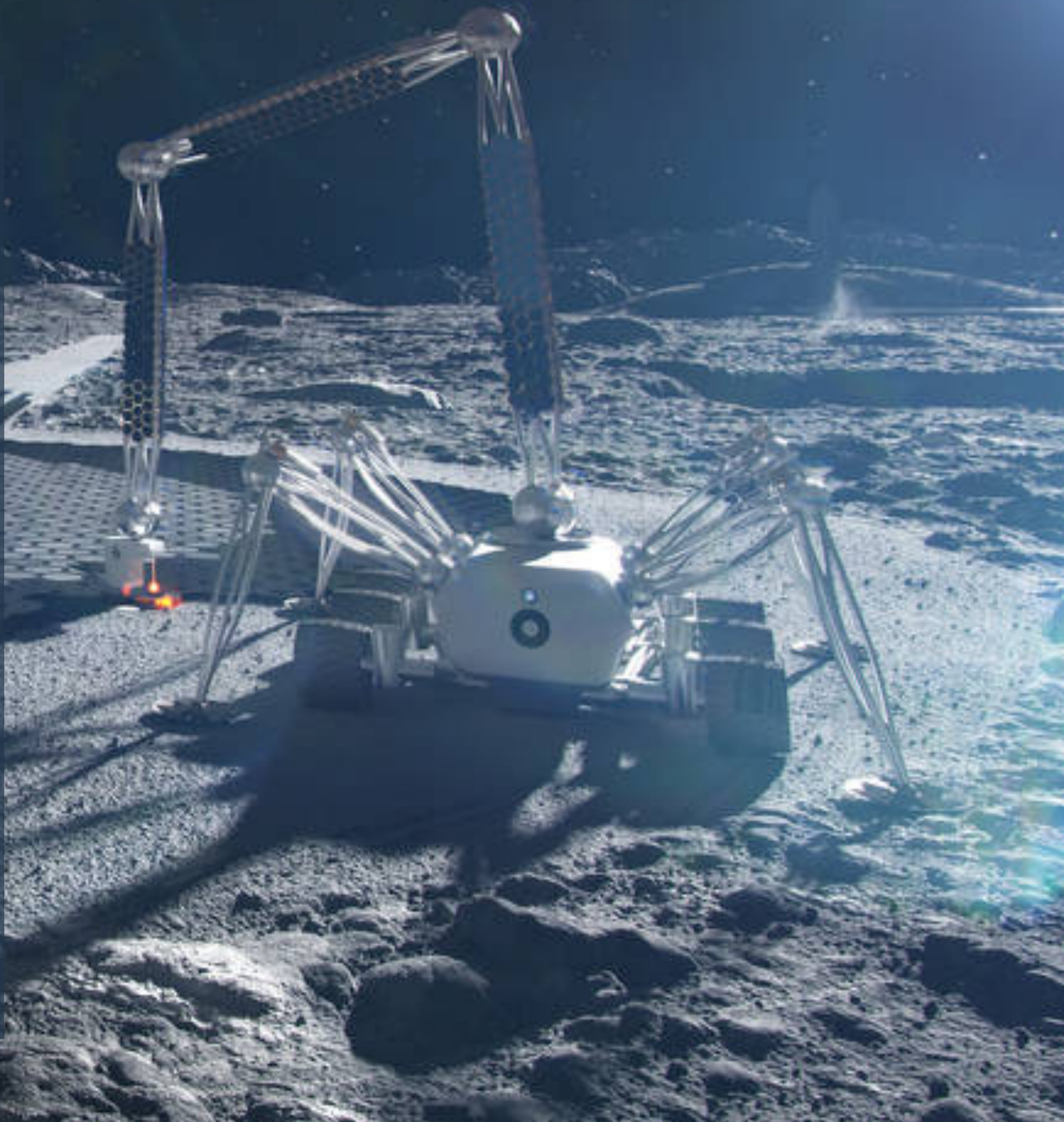


Photo Credit: ICON/BIG-Bjarke Ingels Group

Thank You. Questions?

New **ISRU Envisioned Future Priorities at:**
https://techport.nasa.gov/framework

University & Public Involvement

ISRU Excavation, & Construction Related Challenges

Printed 3D Habitat Challenge
- Design, build habitat elements, and 3D print a subscale habitat
- Phase III completed 2019

Space Robotics Challenge
- Software for autonomous multi-agent ISRU activities: prospecting, excavating, and delivering
- Phase II completed 9/2021

CO_2 Conversion Challenge
- Convert CO_2 into sugars
- Phase I completed
- Phase II completed 8/2021

Watts on the Moon Challenge
- Solutions for energy distribution, management, and/or storage
- Phase I completed 5/2021

Break the Ice Challenge
- Excavate icy regolith in PSR
- Phase I completed 8/2021
- Phase II now open

Lunar PSR Challenge 2020
– 8 university teams; mobility, power beaming, tether, and wireless charging, instrument, and tower
  - Winner: MTU superconducting cable deployment

Lunar Dust Challenge 2021
- Landing Dust Prevention and Mitigation
- Spacesuit Dust Tolerance and Mitigation
- External Dust Prevention, Tolerance and Mitigation
- Cabin Dust Tolerance and Mitigation

Lunar Forge Challenge 2023
- Producing Metal Products on the Moon

Lunar Surface Technology Research (LuSTR)
- 2020. Advanced techniques for extracting and processing of water from lunar soil, or regolith; Methods for determining the distribution and properties of water-bearing regolith
  - 3 teams selected
- 2021. Construction and Regolith beneficiation
  - 2 teams selected

Moon Mars Ice Challenge
- Yearly, university, started in 2017 for Mars ice; added Moon in 2019
- Understand subsurface stratigraphy/hardness
- Extract subsurface water
- 10 teams compete in final 2 day event at LaRC

Lunabotics Robotic Mining Competition
- Started in 2007 following Lunar Excavation Centennial challenge
- Design/build robotic machines to excavate simulated lunar soil
- Teams compete at KSC

Over the Dusty Moon 2022
- Convey regolith 3 m high x 5 m

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***

H_2O Separation, Capture & Transfer → ***Volatile Separation & Storage*** → ***Products from Water/Volatiles***

H_2O Cleanup & Storage → ***Volatile Separation & Storage***

Water Electrolysis → ***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

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.

580 ISRU water cleanup and water quality measurement

576 Separation & Collection of secondary volatile species

1333 ISRU from Secondary Volatiles

572 Long Duration Water Electrolysis

577 Regenerative gas dryers to remove water before liquefaction

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*

Resource Assessment
- 403 Instruments to measure Geotechnical regolith properties in extreme lunar environment
- 404 Instruments to determine local regolith mineral/chemical composition

Excavation & Delivery
- 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

Hoppers, Prep, &Transfer
- 562 Regolith transfer hardware for long duration ISRU operations
- 563 Sensors for evaluating regolith flow during transfer
- 565 Regolith tolerant valves for high temperatures

Oxygen Extraction from Regolith
- 564 Oxygen Extraction from Lunar regolith
- 566 Metal extraction from regolith
- 561 Sensors for realtime monitoring of resource status for ISRU processing operations

Reactant Regeneration
- 1280 Regenerative contaminant removal systems for ISRU Product/Reagent Gas Streams
- 571 Methane production with ISRU

Water Electrolysis
- 572 Long Duration Water Electrolysis

O_2 Drying or Cleaning
- 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

Resource Assessment
- 403 Instruments to measure Geotechnical regolith properties in extreme lunar environment
- 404 Instruments to determine local regolith mineral/chemical composition

Excavation & Delivery
- 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

Hoppers, Prep, & Transfer
- 562 Regolith transfer hardware for long duration ISRU operations
- 563 Sensors for evaluating regolith flow during transfer
- 565 Regolith tolerant valves for high temperatures

Metal Extraction from Regolith
- 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

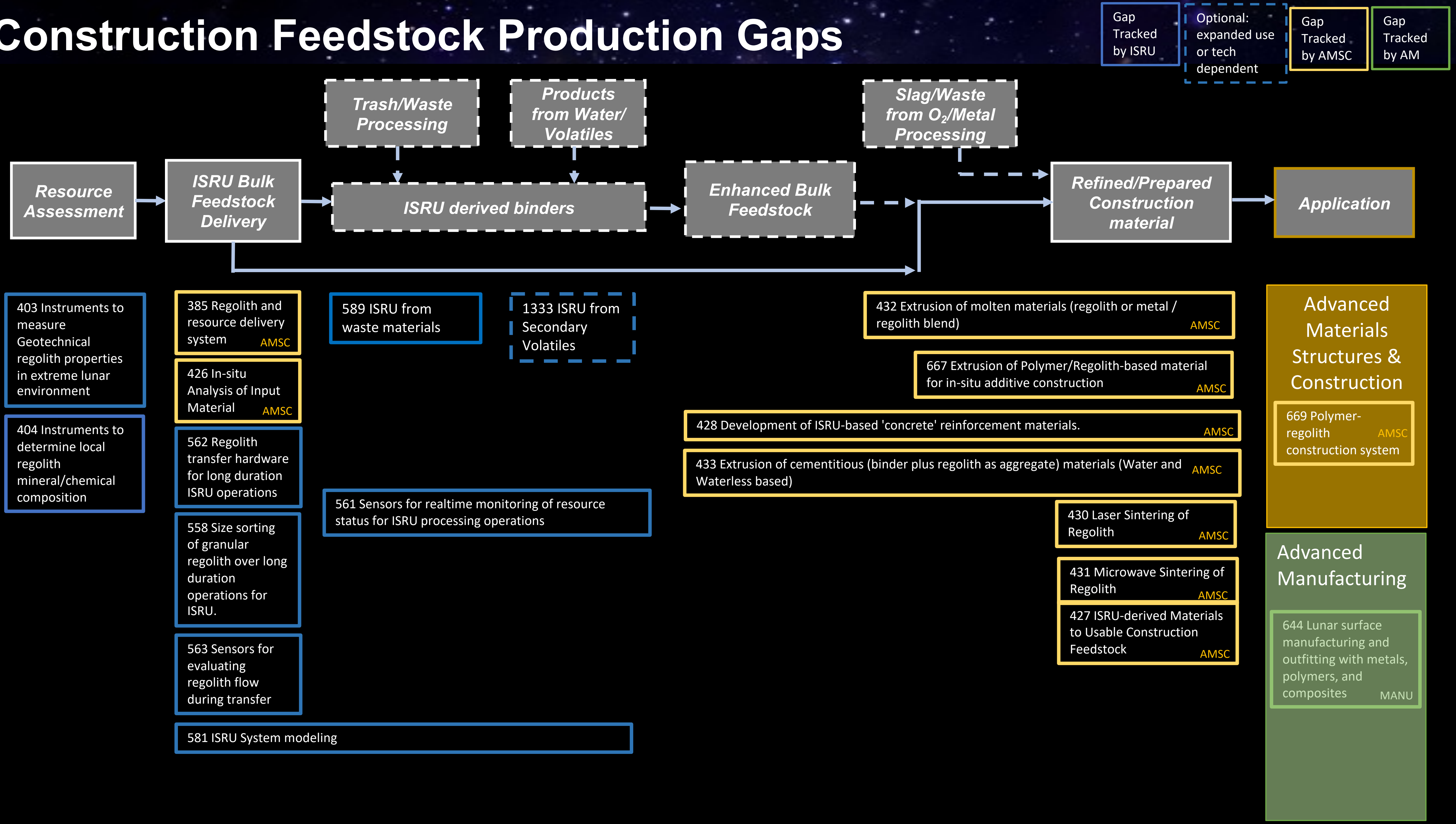
Refinement & Feedstock Preparation
- 427 ISRU-derived Materials to Usable Construction Feedstock AMSC
- 432 Extrusion of molten materials (regolith or metal / regolith blend) AMSC
- 801 Inability to produce manufacturing feedstocks in situ from lunar or Martian materials MANU

Application

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

Cross-cutting
- 558 Size sorting of granular regolith over long duration operations for ISRU.
- 559 Mineral separation/ beneficiation methods for long term ISRU operations
- 581 ISRU System modeling
- 582 Lunar O2 System Integration & Testing

Construction Feedstock Production Gaps



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

Ar & N_2 Separation & Collection

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

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

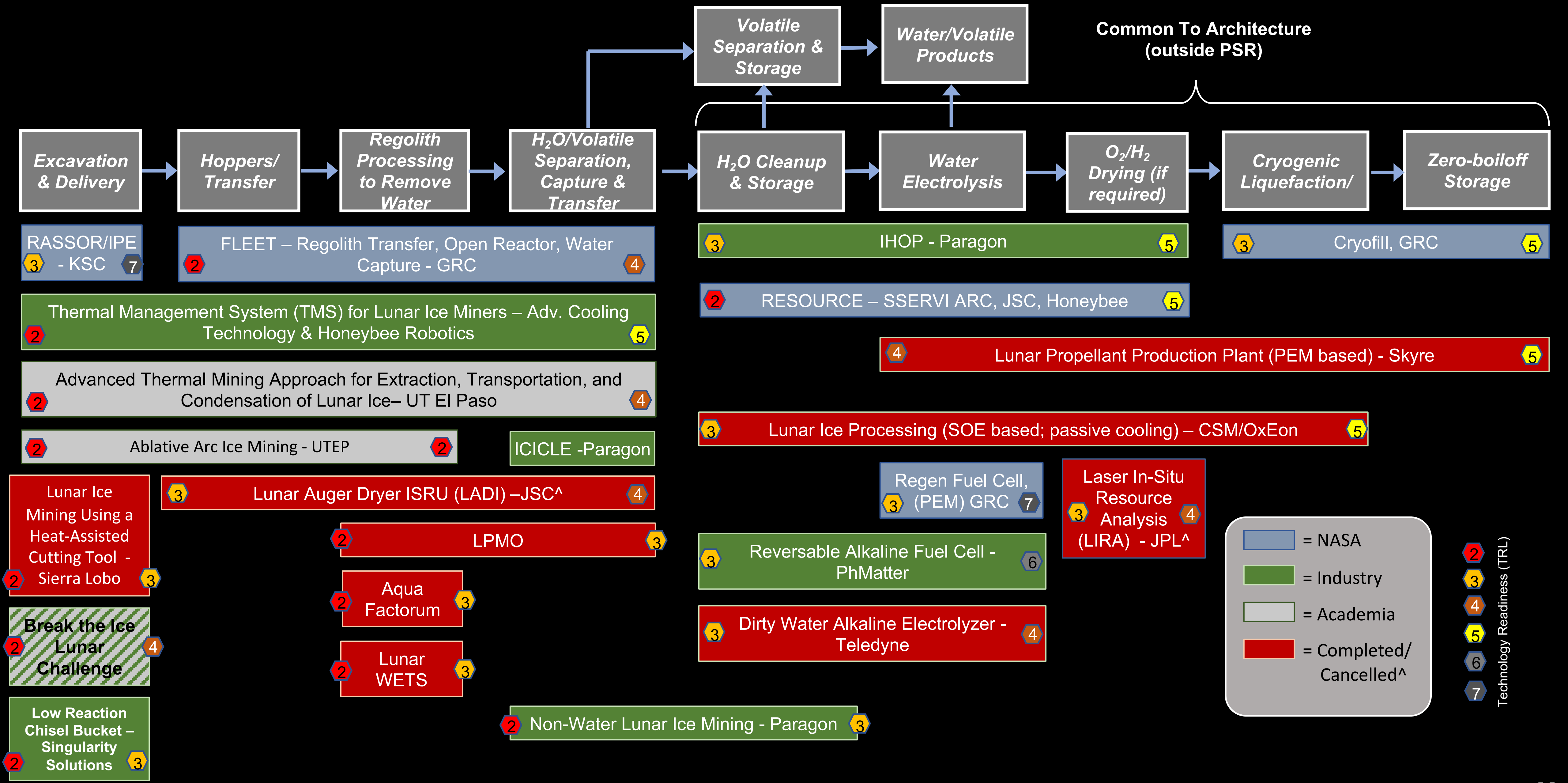
Cryogenic Fluid Management
- 879 Cryogenic Propellant Storage CFM
- 1226 In Situ Cryogenic Fluid Liquefaction CFM

575 Sensors to monitor ISRU process gases

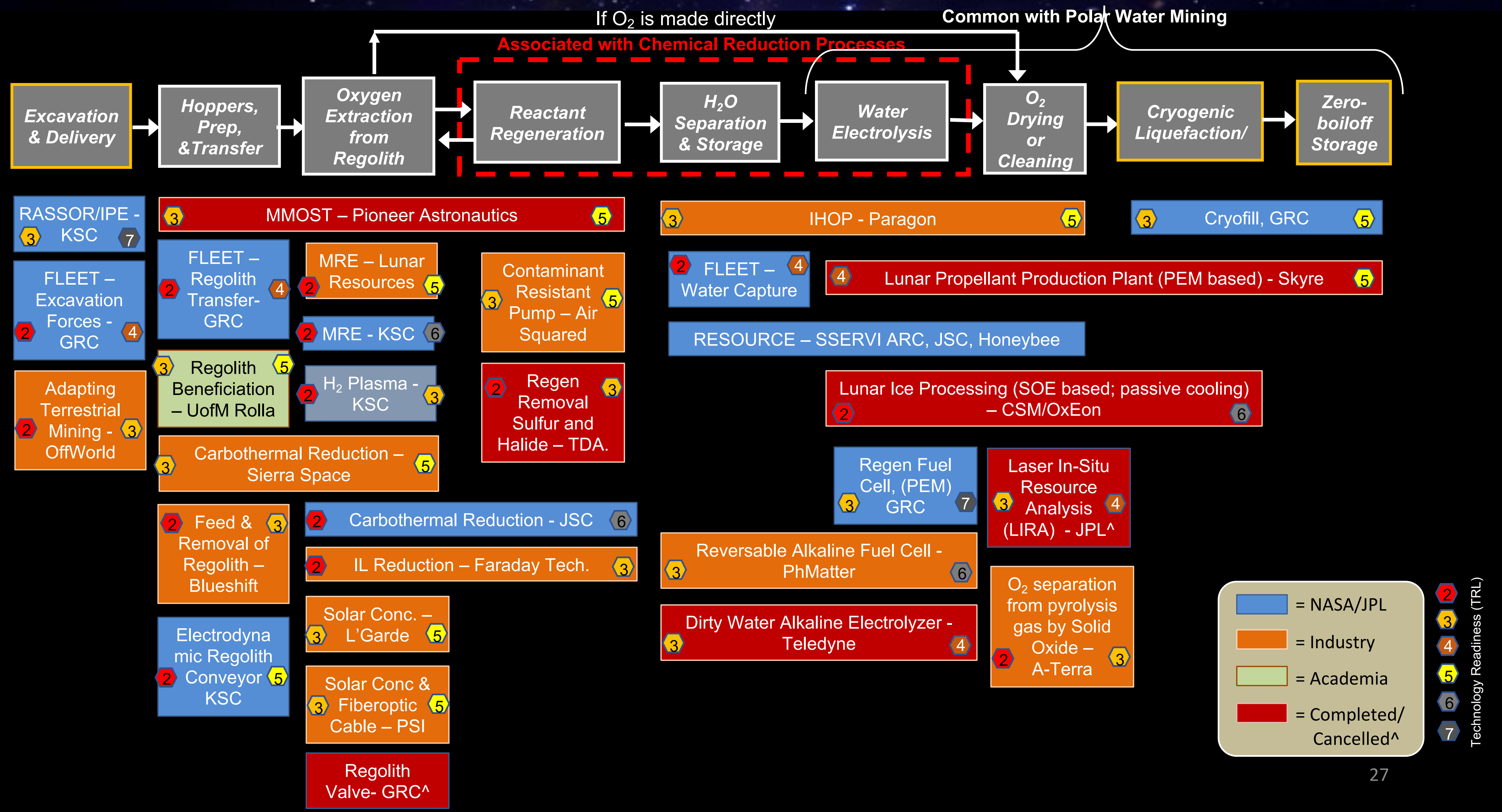
581 ISRU System modeling

1334 Mars ISRU System Level Integration and Testing

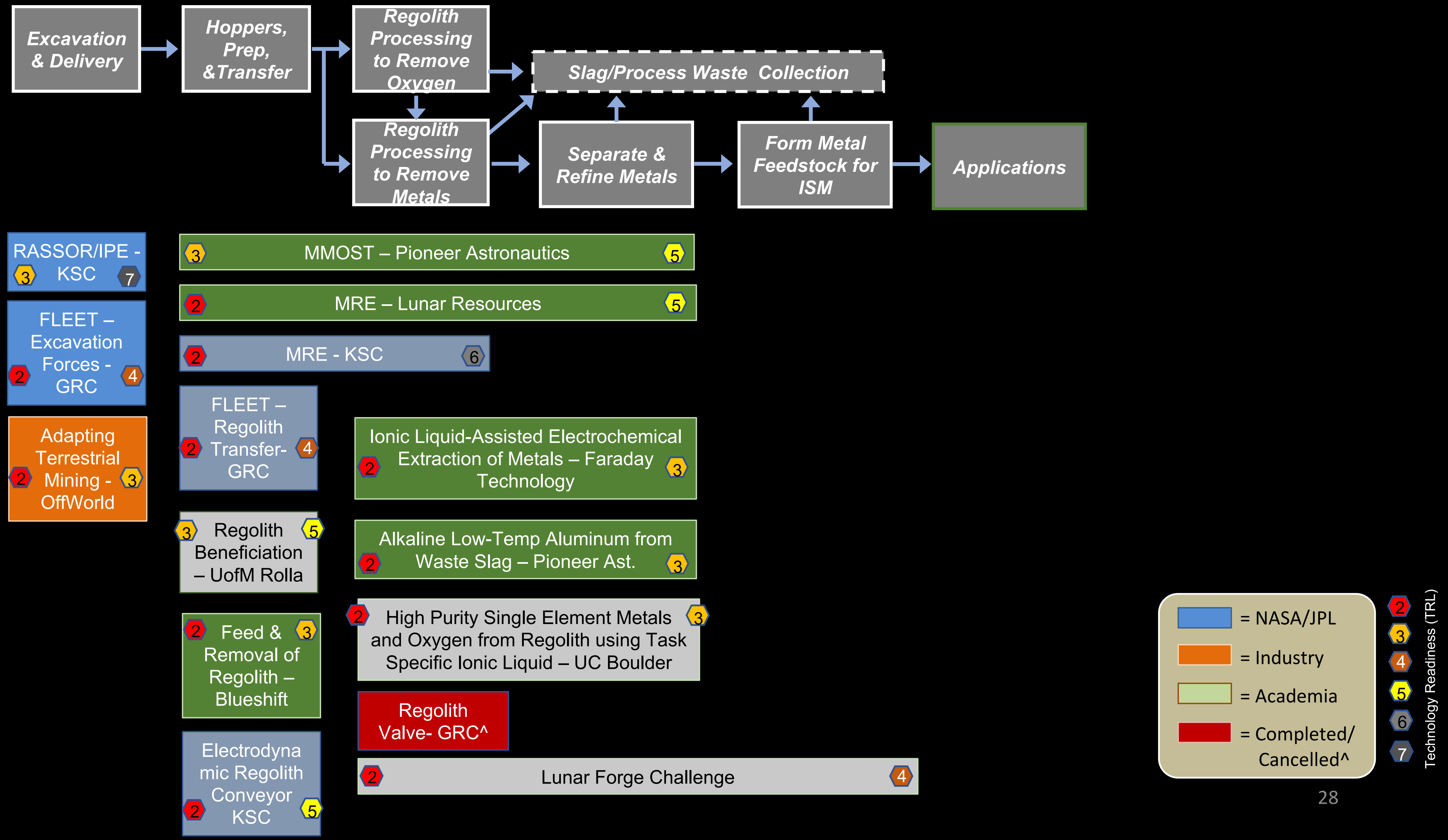
Technology Projects for Water Ice ISRU Pilot Plant



Technology Projects for Oxygen Extraction ISRU Pilot Plant



Technology Projects for Metal/Silicon Extraction



Technology Projects for Manufacturing/Construction Feedstock Production