Autonomy and Robotics Needed for Large-Scale Lunar ISRU and Surface Construction

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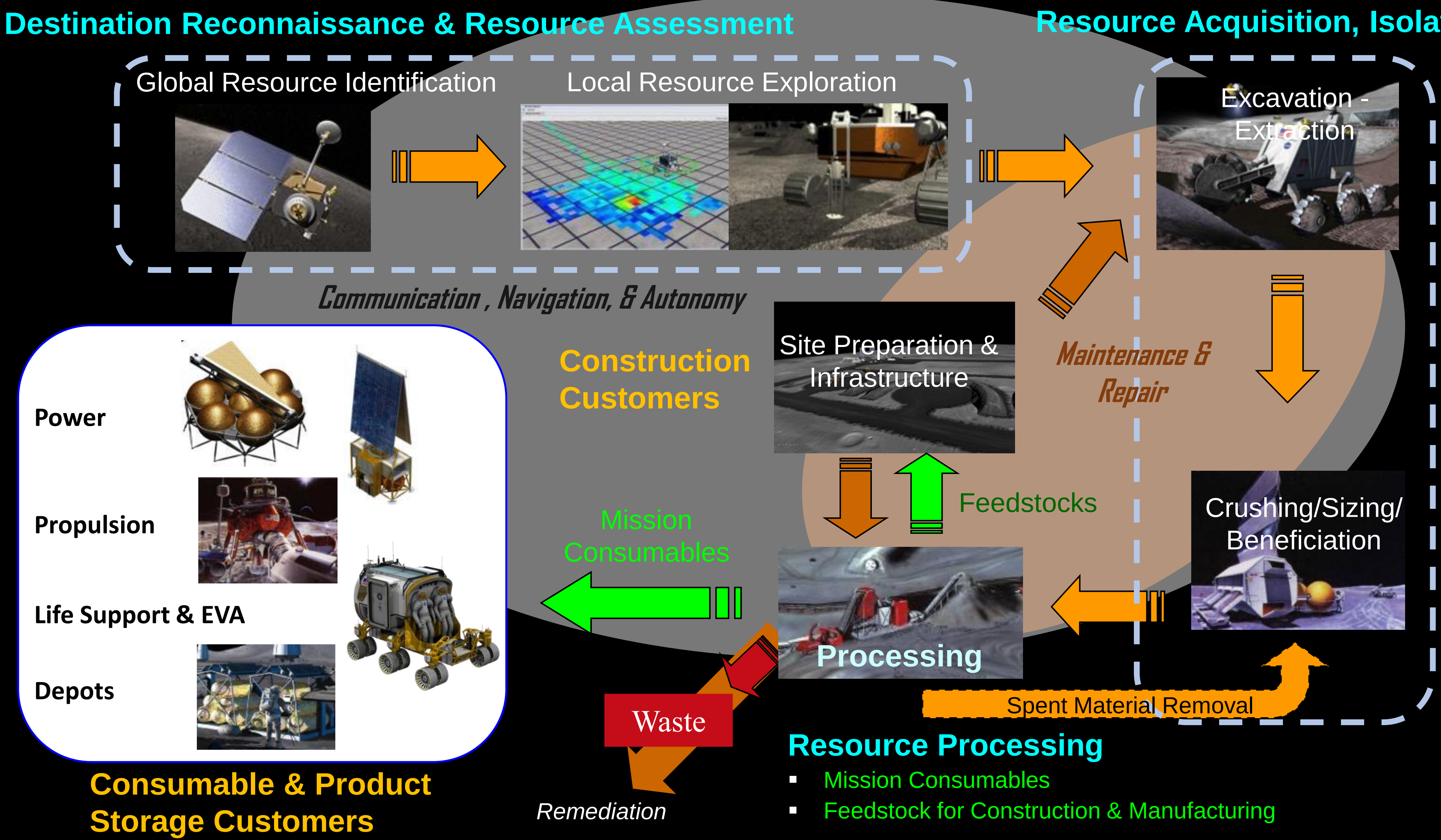
Lunar In Situ Resource Utilization *'Prospect to Product'* Mining Cycle

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



- **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**

Space Mining/ISRU Must Operate as Part of A Larger Architecture

- Elements and interdependencies must be designed with Space Mining product usage in mind from the start to maximize benefits
  - Transition from Earth-supplied to ISRU-supplied
  - Guided by overarching Site Master Plan and Concept of Operations

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

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

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

Space Mining

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

Maintenance & Repair Logistics Management
- Replacement parts (P)
- Feedstock (S)

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

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

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

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

Artemis Architecture Segments

HUMAN LUNAR RETURN

Initial capabilities, systems, and operations necessary to reestablish human presence and initial utilization (e.g., science) on and around the Moon.

FOUNDATIONAL EXPLORATION

Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.

SUSTAINED LUNAR EVOLUTION

Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

HUMANS TO MARS

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

Artemis Architecture Segments

HUMAN LUNAR RETURN

Initial capabilities, systems, and operations necessary to reestablish human presence and initial utilization (e.g., science) on and around the Moon.

Demonstrate ISRU

Locate Resources

FOUNDATIONAL EXPLORATION

Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.

Map Resource Reserves

Utilize ISRU

SUSTAINED LUNAR EVOLUTION

Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

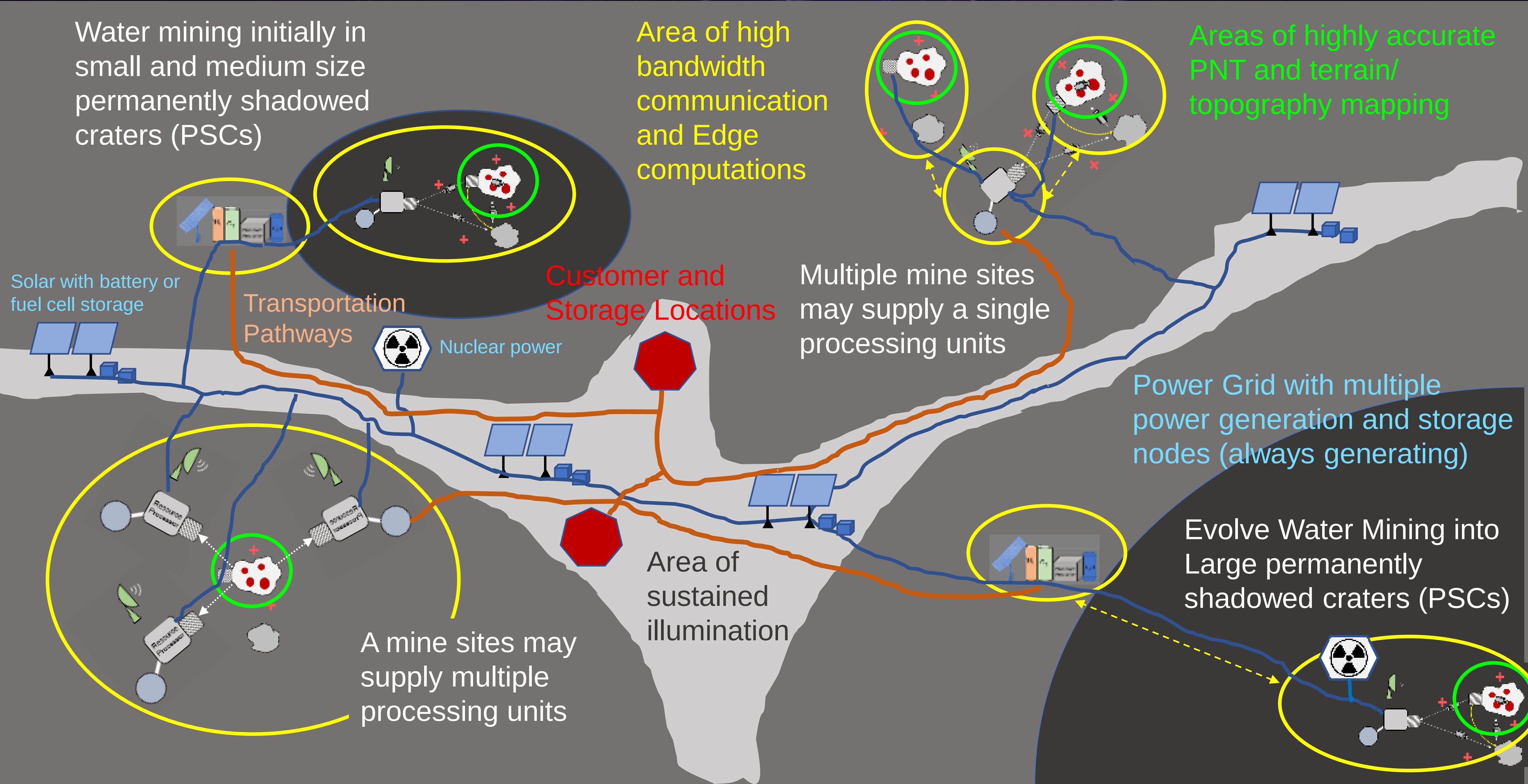
Map Water Resources

Demonstrate & Utilize ISRU

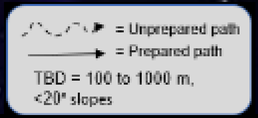
HUMANS TO MARS

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

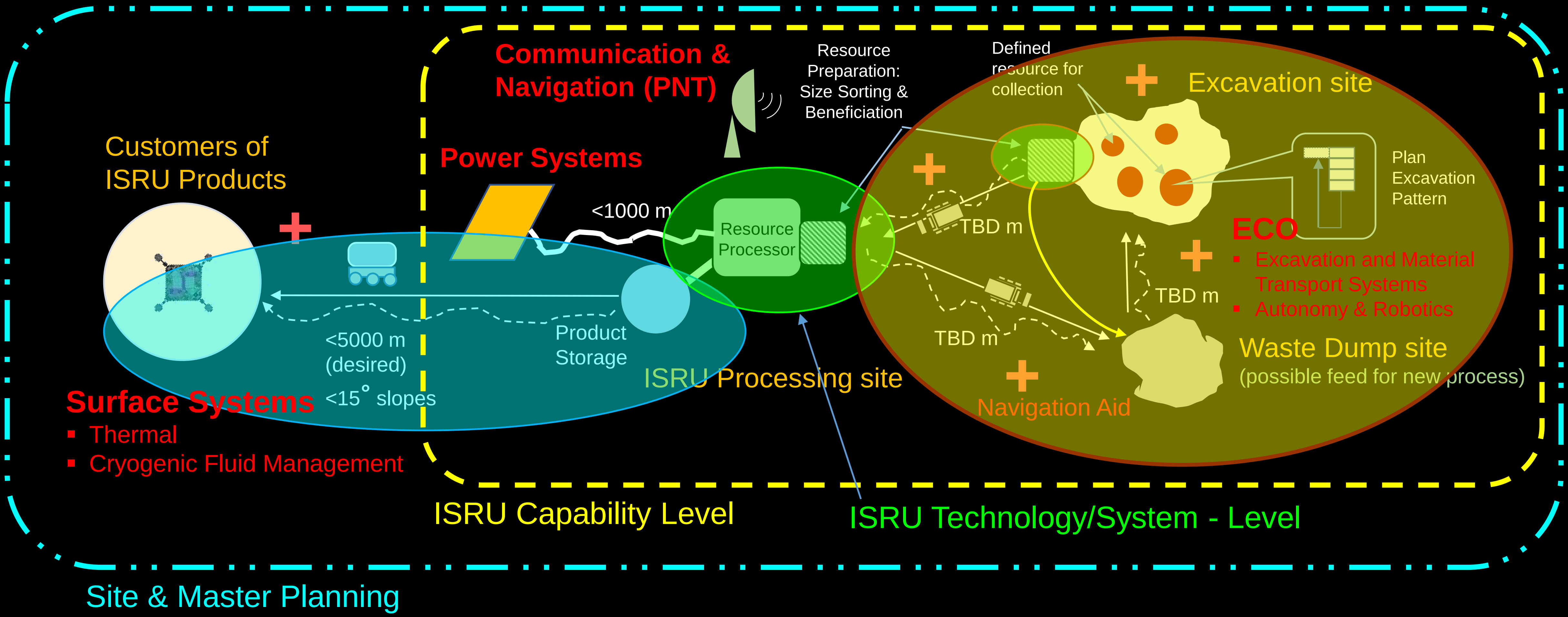
Notional Regional-Scale Lunar ISRU and Infrastructure



Lunar ISRU System and Concept of Operations



Highlighting Collaboration & Coordination Between NASA Disciplines



Two levels of Development, Integration, and Testing

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

ECO = Excavation, Construction & Outfitting
PNT = Position, Navigation & Timing

Lunar Mining and Processing Infrastructure Questions

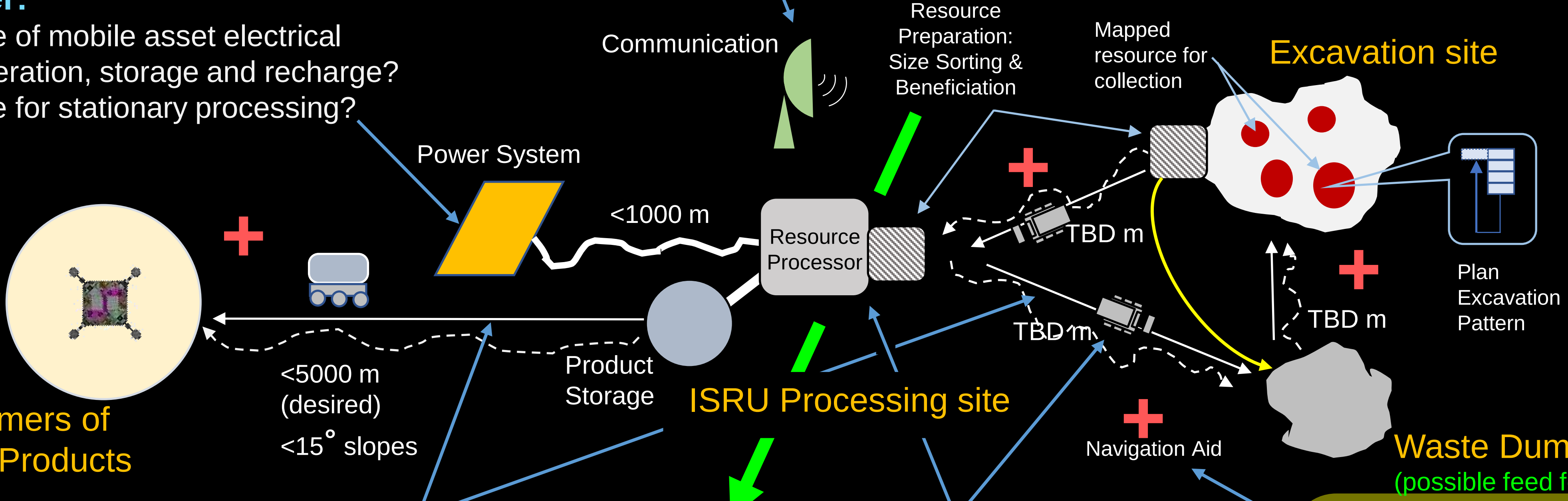
Need to coordinate across Architecture, Elements, and Disciplines

Communication: What frequency, bandwidth, throughput is needed for?:
- Mobile asset control
- Fixed asset control
- Big Data
- Delay-Tolerant Networking

Tied Together

Big Data: What is needed for?:
- Tracking minerals from excavation to dumping
- Updating Excavation Plan based on tracking minerals
- Change operations to optimize around tracked minerals
- Understand performance and maintenance trends
- On-site/asset vs remote analyses; Space vs Terrestrial computers

Power:
- Type of mobile asset electrical generation, storage and recharge?
- Type for stationary processing?



Resource Extraction: What resource & type of system?:
- Granular vs hard/icy
- Surface or subsurface
- Combined or separate excavation/hauler

Resource/Product Delivery: What scale and distance of operation causes?:
- Mobile units, augers/conveyors, or pipes
  - Construction of roads for mobile units
  - Construction of rails
  - Construction of pipes

Platform/Vehicle Autonomy: What level of self control/awareness is needed:
- Operations
- Traverses
- Avoidance
- Coordination with other assets

Tied Together

Navigation: What type of passive/active aids should be used for?:
- Traverses
- Excavation operations
- Dumping/delivery operations

Areas of Commonality Between Terrestrial and Space Mining to Achieve the 'Mine of the Future'

Resource Assessment – Mapping – Valuation

1. High confidence in resource reserves

Infrastructure for Mining and Processing

2. Continuous renewable power at multiple and remote locations
3. High accuracy positioning, navigation, and timing (PNT) in non-GPS environment
4. Secure, distributed, high bandwidth communication network
5. Rugged on-board processing and Edge computing

Operations for Mining and Processing

6. Data rich environment with real-time measurements
7. High level of autonomy for all operations
8. Minimize logistics and ease maintenance/On-site manufacturing
9. Electrification of all mechanisms and platforms

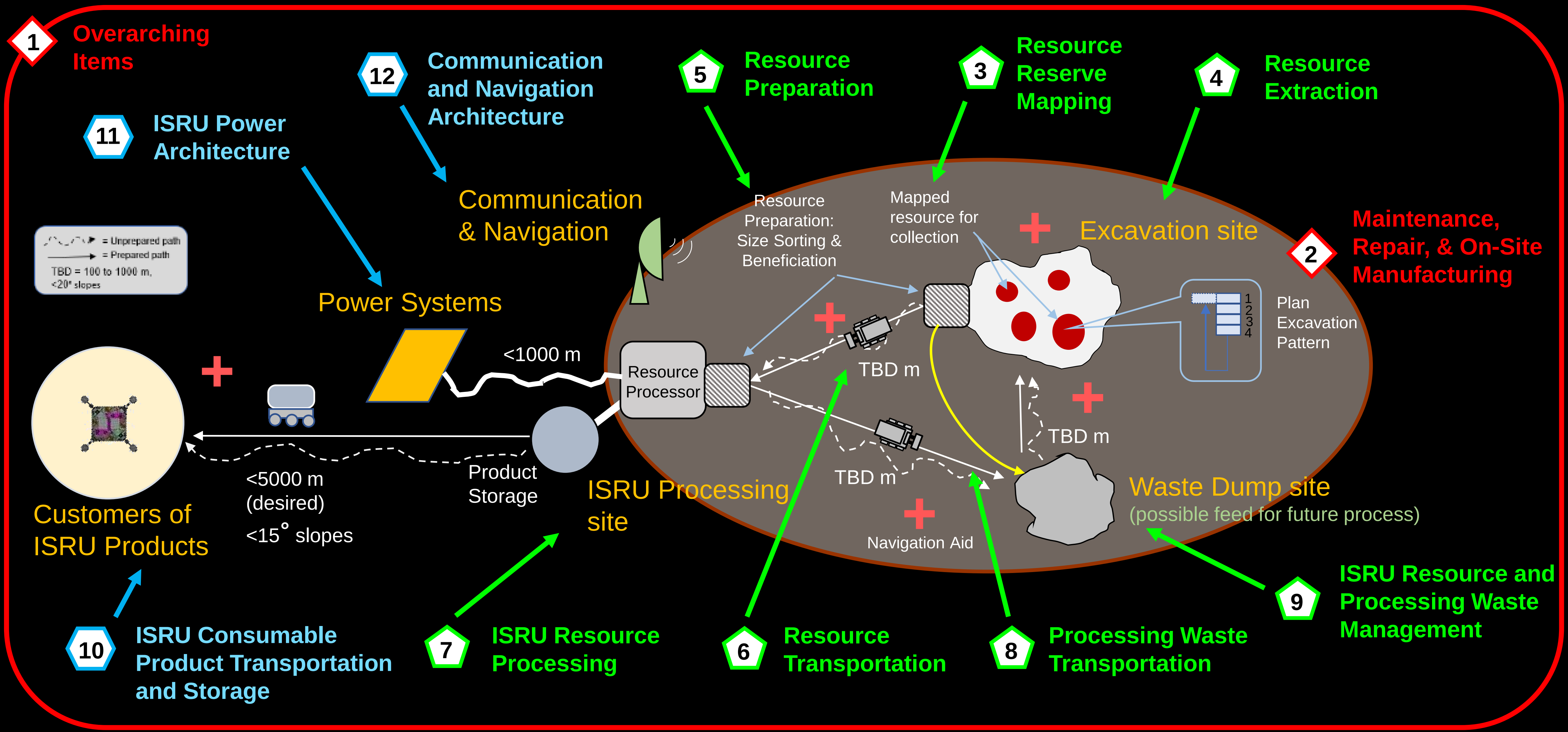
Safety

10. Minimize on-site human/crew involvement, esp. high-risk operations
11. Minimize number and severity of safety and time critical operations

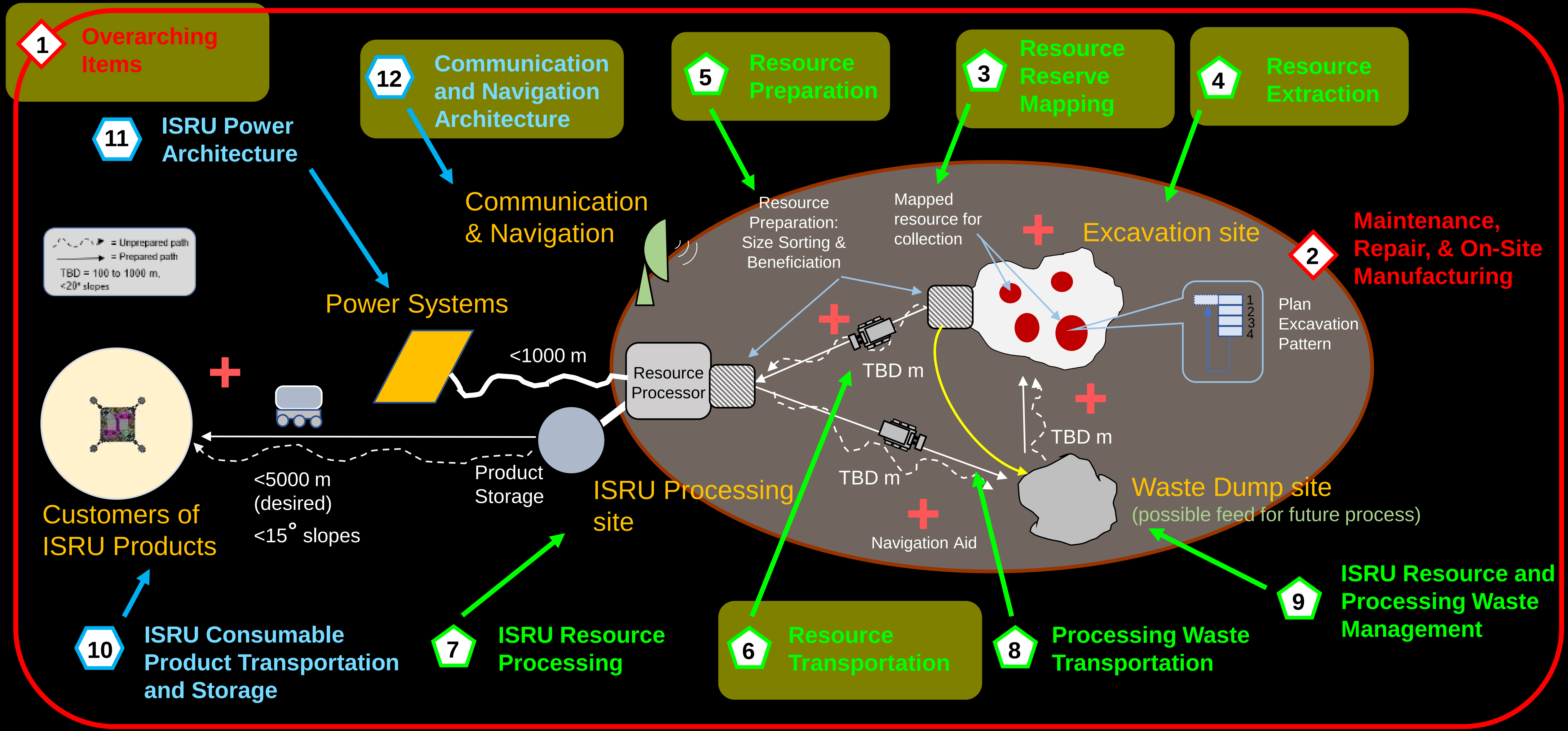
Environmental Impact

12. Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment
13. Mitigate environment impacts on hardware/operations and vice versa
14. Continuously and distributed environmental monitoring
15. Remediate sites at completion of operations

Lunar ISRU System and Concept of Operations



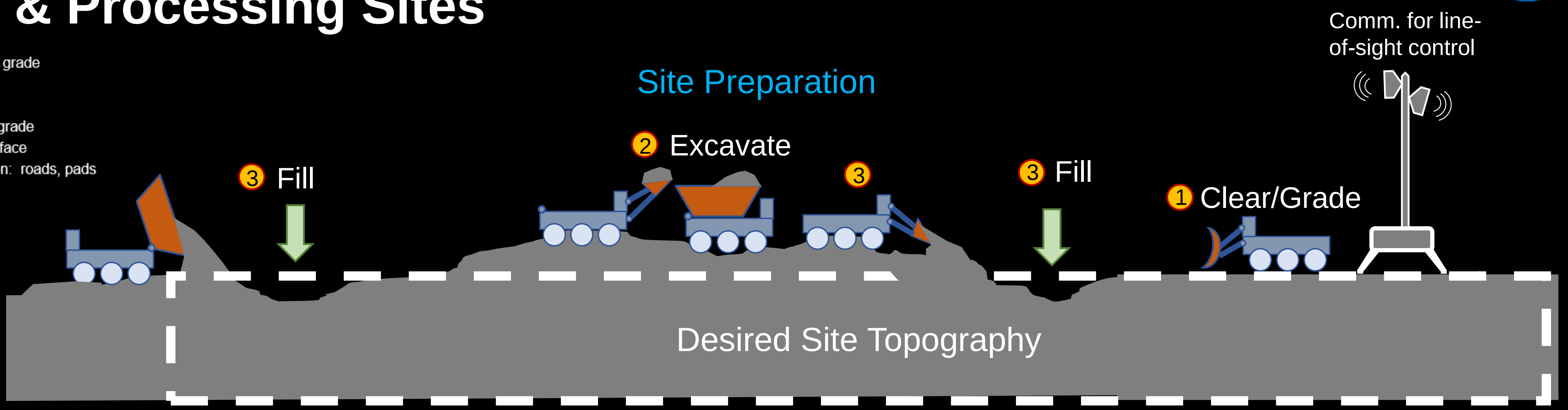
Lunar ISRU System and Concept of Operations



Performing Site Preparation and Construction Activities At Mining & Processing Sites

1. Clear: remove rocks, grade
2. Excavate high areas
3. Dump in depressions
4. Bring surface to final grade
5. Compact/stabilize surface
6. Horizontal construction: roads, pads

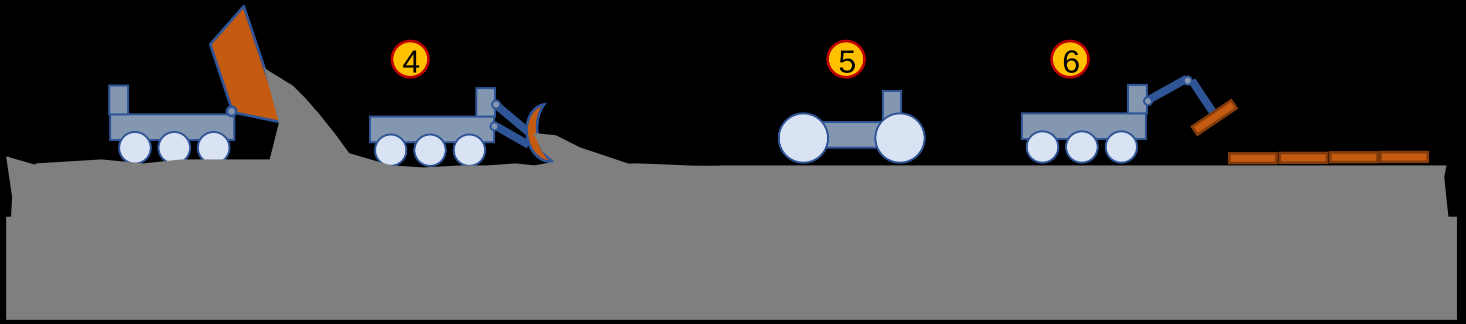
Site Preparation



Remote Operated/Autonomous Vehicle Operations Requires:

- High accuracy information on terrain topography on continuous bases
- High accuracy position, navigation, and timing (PNT) for mobile units and regolith/construction operations
- Advanced space computers, avionics, and software for remote/autonomous operations
- High bandwidth communications on-site and to/from Earth
- Dust insensitive power storage; fast recharging
- Long-life and maintainable mobile units and implements

Horizontal Construction: Fine Grade & Flat Structures



Lunar ISRU System and Concept of Operations

1 Overarching Items

- **Design elements with maintainability and end-of-life in mind from the start. This will include:**
  - Maximize use of common elements: motors, controllers, sensors, connectors and interfaces, latches/attachment points
  - Maximize use of modular/swappable elements/units
  - Hardware from multiple entities (countries and companies) will need to work effectively with each other
  - Promote in situ manufacturing of replacement parts and recycling of high-wear elements (see 12. Maintenance and Repair)
- **Control: Software & Autonomy**
  - Develop intelligent and integrated control hierarchies to allow operations to be more efficient and reactive to change or new information.
  - Consider dynamic daily and 'seasonal' optimization
  - Buffers are needed for material flow and power
  - Transmitting, collecting, managing, and analyzing large amounts of data will be required
  - High levels of autonomy and data rich environment with near real-time measurements will require rugged on-board processing and Edge computing
  - Some level of 'self-awareness' of all ISRU mining and processing operations and surroundings is required to prevent or inhibit operations if unsafe conditions arise (i.e. conditions where damage to itself or other assets/people could occur)
- **Mission and Crew safety are paramount.**
  - System designs need to minimize time critical safety operations, and on-site human/crew involvement in hazardous/high-risk operations needs to be minimized with appropriate safety inhibits when crew are present
- **Sustainability and Responsible Operations should be a Focus from the Start**
  - Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment
  - Mitigate environment impacts on hardware/operations and vice versa
  - Distributed environmental monitoring on a continuous basis
  - Remediate sites at completion of operations
  - Circular economy; reuse and minimize waste
- **Technologies and systems need to be scalable and evolvable from initial commercial operations to large scale**

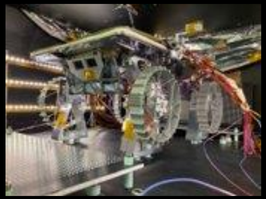
Lunar ISRU System and Concept of Operations

3 Resource Reserve Mapping

- Need Geotechnical, Mineral/Chemical, and Volatile Characterization Instruments down to 10 meters
- Examples of instrument/mission types for lunar resource exploration

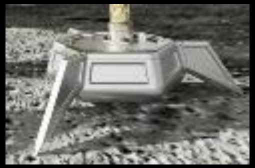
Coordinated Subsurface Assessment

- Multi-rovers with one or more instruments
  - Active and/or passive seismic
  - Ground penetrating radar
  - Gravity
  - Dielectric
  - Induced polarization
  - Neutron



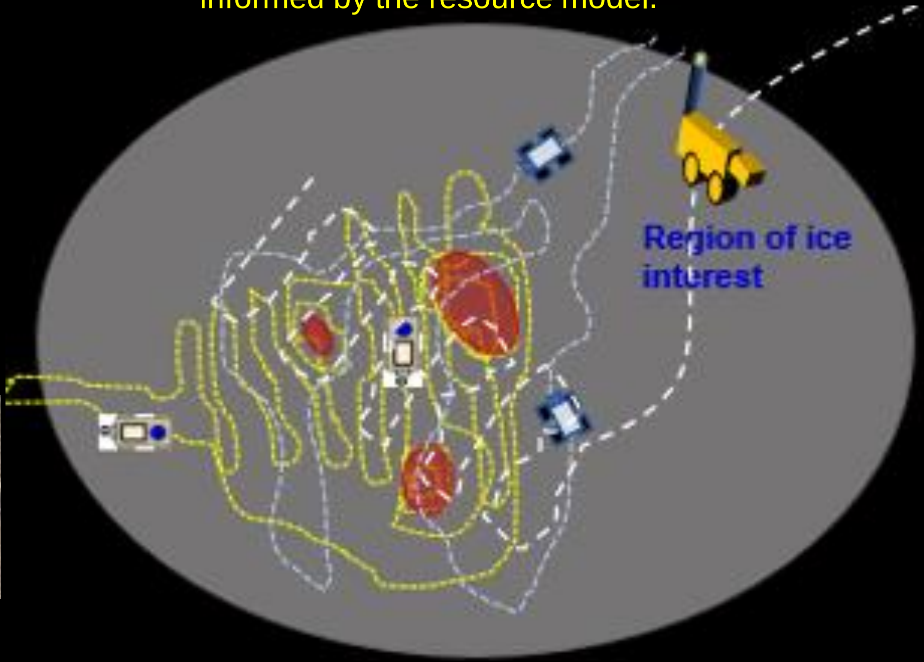
CADEE - JPL
Multi-rover GPR

Juno multi-rover
GPR - Neptec



Repositionable seismic sensors - FLEET

Geochemical and volatile analysis (assaying) is performed on certain drill holes/ samples to build knowledge and confidence, since the local geology may deviate from the coarse predictions informed by the resource model.



Micro-rovers or hoppers with neutron spectrometers

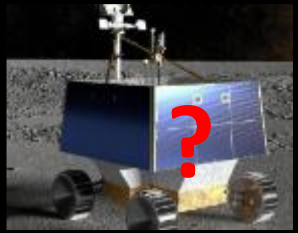
MoonRanger - Astrobotic

MAPP – Lunar Outpost

Micro-NOVA Hopper – IM

Coordinated Subsurface Measurement

- Multi-instrument mobile platforms
  - Subsurface samples (augers, cores)
  - Downhole measurements



VIPER

LUPEX - JAXA

End States:

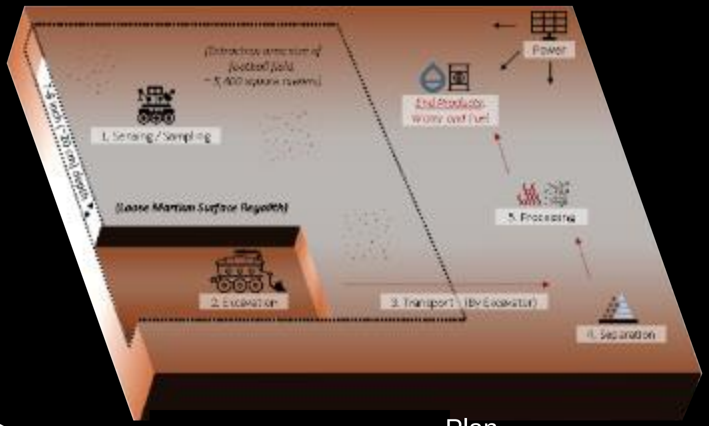
- Need highly accurate PNT and terrain/ topography mapping
- Need high bandwidth communication for multi-asset control and Edge computations for resource exploration data analysis, predictive model updating, and adaptive resource mapping and optimization

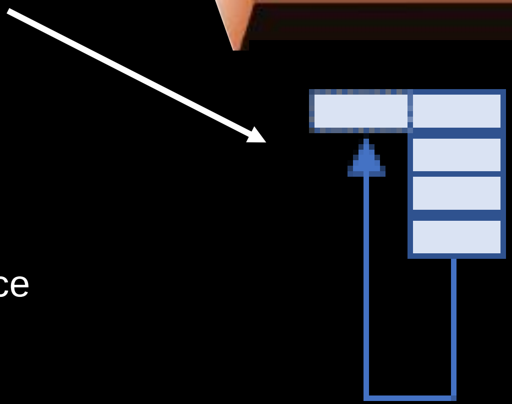
Lunar ISRU System and Concept of Operations

4 Resource Extraction Planning and Operations

Overview of Operations

- **Extraction of resources in lunar regolith most likely through surface 'open pit' mining. Initially most likely not very deep.**
  - Need to consider long term production and product demand
  - Desired footprint of the excavation site along with mineral distribution will factor into mining plan
- **Excavation activities will most likely be performed by multiple – modular assets (instead of one big unit) requiring coordination.**
  - Need to plan and operate excavation tasks in series and align with previous extraction location
  - May also help reduce mining footprint and focused extraction
- **Track each vehicle location, performance, and resources carried for managing/optimizing extraction and delivery operations and support hazard mitigation and maintenance**
  - Need high bandwidth communication for multi-asset control and Edge computations for resource tracking, predictive model updating, and excavation planning





Plan Excavation Pattern

End States

- Excavation/extraction units tailored specifically to regolith/resource physical characteristics and maintenance repair strategy
- **Need highly accurate PNT and terrain/ topography mapping (#11)**
  - Need centimeter-level control of excavation operations for autonomous mining/extraction and excavation plan
  - Need centimeter-level control for regolith delivery to bins/hoppers for 5. Resource Preparation and 6. Resource Processing
  - Need centimeter-level topography measurements of the excavation/extraction site for continuous extraction planning optimization
- **Supervised autonomy with on-board hazard avoidance of surface features and assets**

Lunar ISRU System and Concept of Operations

6 Resource Transportation

Operation and Infrastructure Evolution

Initial:

- Mobile platforms. May be same asset used for excavation
- Traverse over unprepared surfaces
- PNT: Minimal. Reference tied to initial lander. On-board capability?
- Comm?

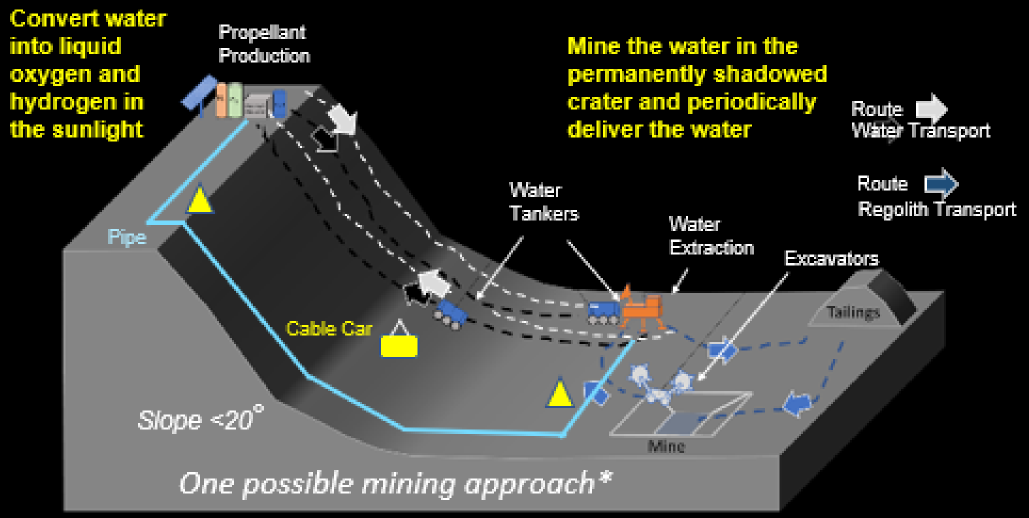
Intermediate – Solid Material

- Dedicated Mobile platforms or Short distance rail or conveyor
- Prepared and maintained traverse paths or traverse infrastructure
- PNT?
- Comm?

End States

- Dedicated rails/conveyors for solid material
- Pipes for liquids/gases
- PNT?
- Comm?

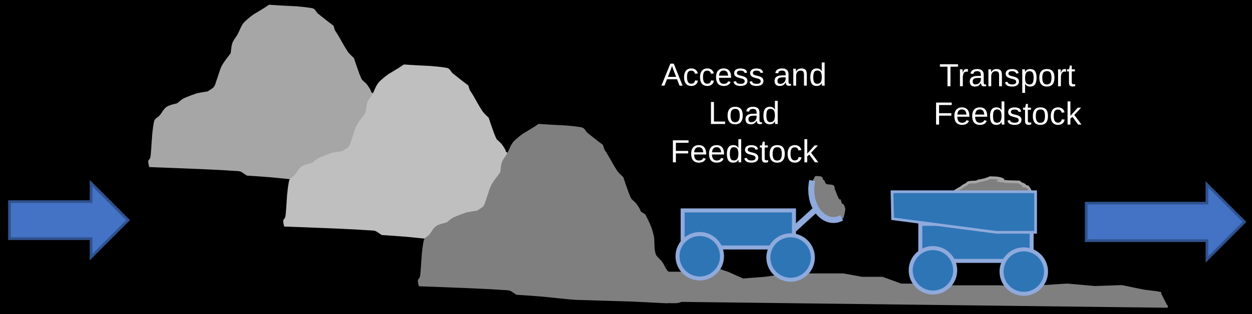
Water Transportation



*Assumes customers for water & O_2/H_2 are outside of the PSR

Granular Material Transportation

From
5. Resource Preparation



Stockpile and Store Feedstock

Transfer Feedstock to
7. Resource Processing & Construction Systems

Lunar ISRU System and Concept of Operations

12 Communication and Navigation Architecture

Navigation and Control includes Positioning, Navigation, Timing, and Hazard Avoidance

- **Remote/Autonomous Operations require preparation**
  - Terrestrial mines typically require prepared roads, ramps in and out of the excavation site
  - Need accurate map of terrain to TBD slope and height accuracy
    - Site-level terrain/subsurface measurements (aerial photography, lidar, or radar scanning) with TBD slope and height accuracy are needed at semi-regular intervals for assessing changes and for position and navigation
  - Start and end locations need to be established before operations began including electric ‘keep out’ fence/barrier surrounding operations
  - Excavation/dozing seem to best operate in long straight lines.
    - Short and radial lines were considered difficult (possible area of joint development for lunar site preparation)

- **Communications and Position, Navigation, and Timing (PNT) are drivers for remote operation**
  - Amount and type of data (Video and operation data) from semi-autonomous tractor systems (SATS) for operation drive communication requirements
    - Need to consider all the remote asset types and numbers that need to be operated and tracked (significantly more than current Artemis campaign is considering)
    - Both on-board and local/situational awareness cameras are needed for remote operators
  - Local position, navigation, and timing (PNT) capabilities are critical for remote operation and meeting cost and performance objectives
  - Real-time on-board PNT measurements with TBD accuracy

- **On-board and Remote Operations are strongly influenced by Communication and Avionics capabilities**
  - Increased time delay for lunar operations will drive need for increased autonomy/reduced remote operator ‘real-time’ control
  - ‘Big Data’ needs to continually refine understanding of ore body and track all product/waste streams
  - On-board Machine Learning (ML) and processing/data manipulation capabilities (drives on-board avionics and software) needs to be balanced with data transmission requirements and capabilities

Presentation Summary

- **An important aspect of achieving the longer-term vision of the Artemis program is to better understand and characterize the resources on the Moon and Mars and learn how to extract and use these resources to for human exploration and the commercialization of cis-lunar space.**

- **Through the extraction and processing of resources into mission commodities such as rocket propellants, life support consumables, and fuel cell reactants, ISRU enhances and evolves the cis-lunar, lander, and surface transportation systems required for human exploration; expanding and enhancing HOW humans get to, explore, and return from the Moon.**

- **Starting in the Artemis Foundational Exploration (FE) segment and becoming fully operational in the Sustained Lunar Evolution (SLE) segment. ISRU and surface construction systems will evolve from small-scale technology demonstrations and end-to-end Pilot Plant system demonstrations to full-scale commercial operations.**

- **Large-scale ISRU and Surface Construction will require significant advances in Robotics and Automation**

- **Areas of commonality between terrestrial mining and space ISRU have been identified, of which six (6) are highly linked to increasing and evolving robotic and autonomous capabilities for terrestrial and space mining applications**
    1. High accuracy positioning, navigation, and timing (PNT) in non-GPS environment
    2. Secure, distributed, high bandwidth communication network.
    3. Rugged on-board processing and Edge computing.
    4. Data rich environment with near real-time measurements
    5. High level of autonomy for all operations (esp. remote)
    6. Minimize on-site human/crew involvement, esp. high-risk operations.

Questions?