National Aeronautics and Space Administration

In-Situ Resource Utilization (ISRU) Concepts for a Retrieved Asteroid in a Lunar Distant Retrograde Orbit (LDRO)

Space Resources Roundtable (SRR) / Planetary & Terrestrial Mining Sciences Symposium (PTMSS)

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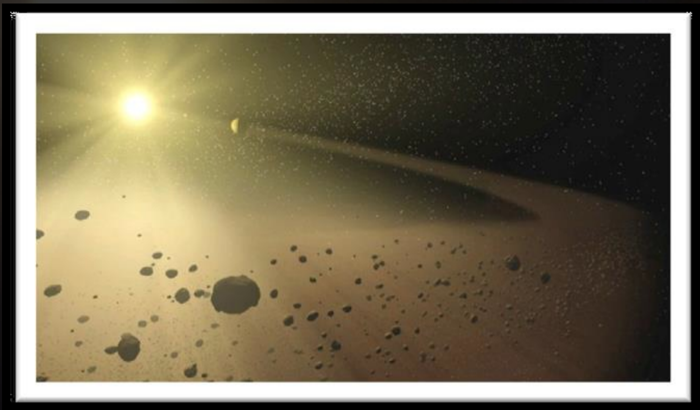
Asteroid Strategy

The President announced in April 2010 a human mission to an asteroid. The budget leverages NASA's human and robotic activities for the mission and also accelerates efforts to address potentially hazardous asteroids:

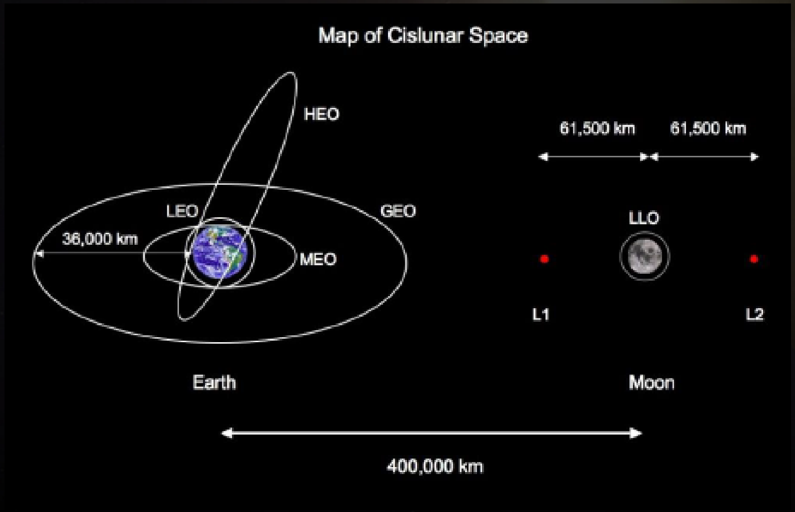
- To protect our planet
- To advance exploration capabilities and technologies for human space flight
- To learn how to best utilize space resources.

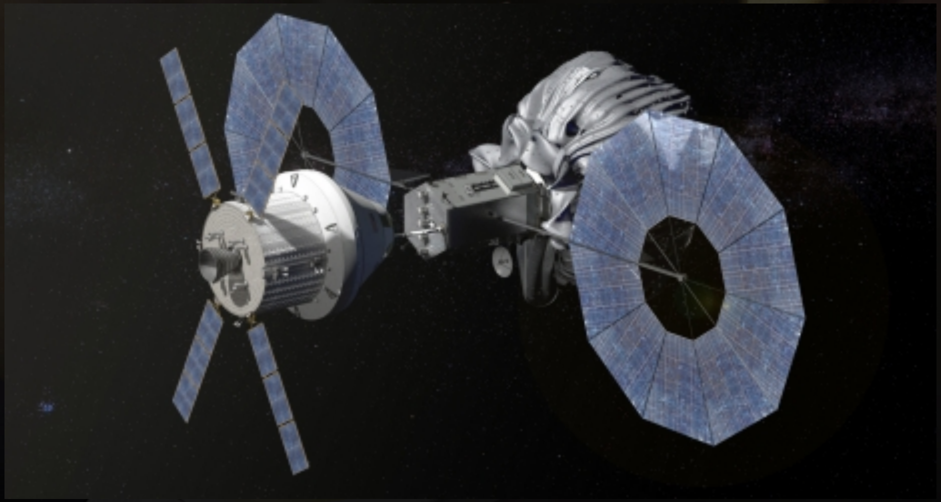


The FY14 budget aligns relevant portions of NASA's science, space technology, and human exploration capabilities to plan for the mission. NASA will build on a rich history of engaging citizen scientists, researchers and individual innovators in this quest.

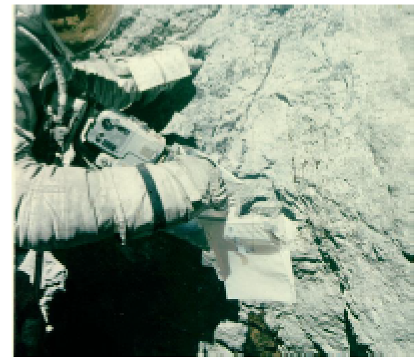
Asteroid Redirect Mission (ARM) Concept

- Capture and redirect a 7-10 meter diameter ~500 ton Near Earth Asteroid (NEA) to a stable orbit in Trans-Lunar Space
- Enable astronaut missions to the asteroid as early as 2021
- Parallel and forward leaning development approach



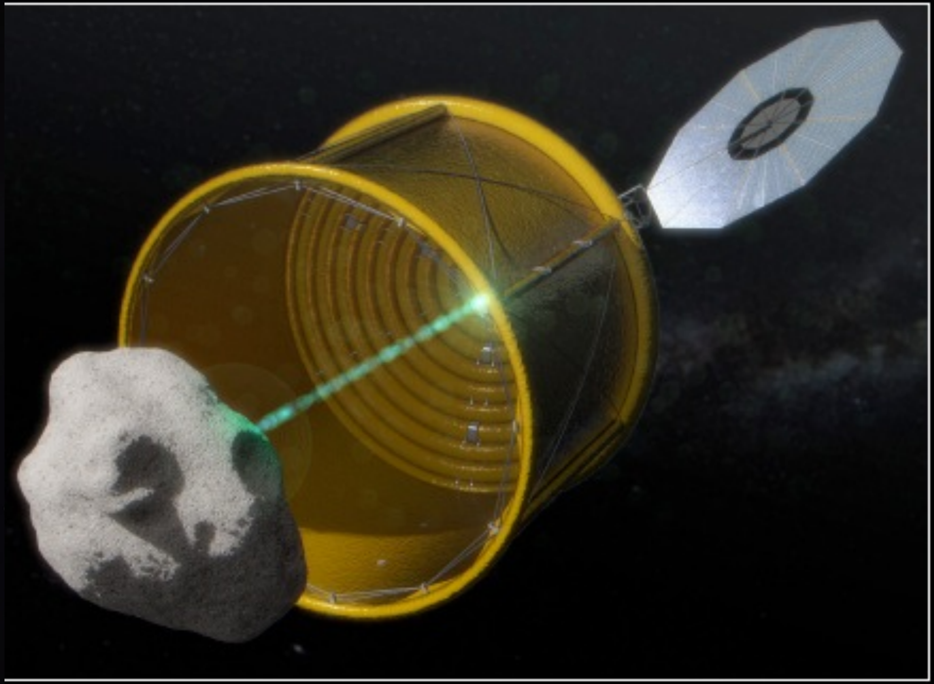


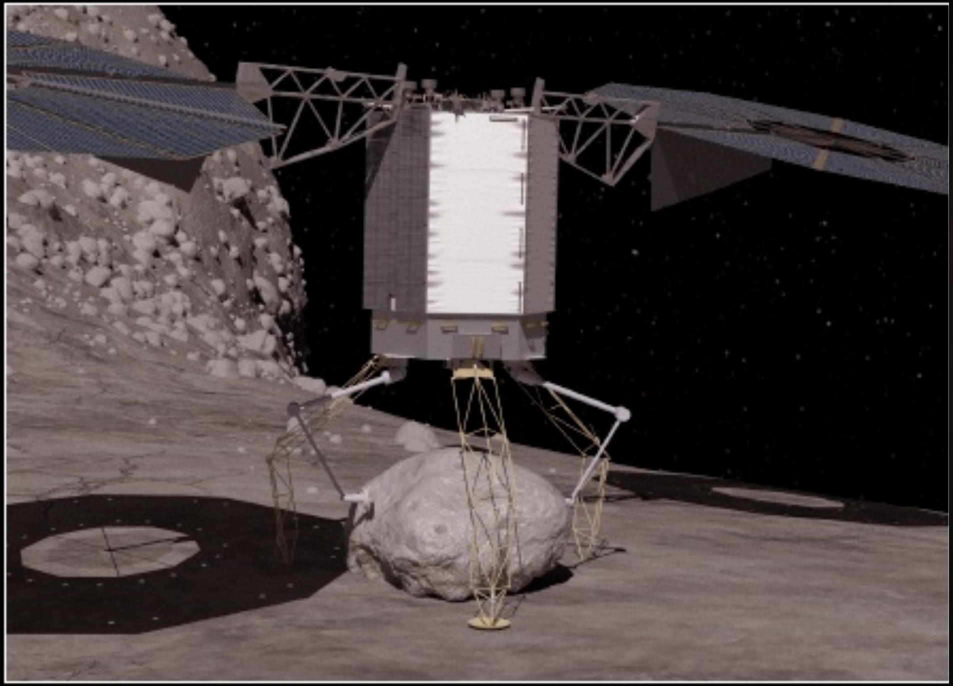
Three Main Segments

Identify	Redirect	Explore
		
Asteroid Identification Segment:	**Asteroid Redirection Segment:**	**Asteroid Crewed Exploration Segment:**
Ground and space based NEA target detection, characterization and selection	Solar electric propulsion (SEP) based asteroid capture and maneuver to trans-lunar space	Orion and SLS based crewed rendezvous and sampling mission to the relocated asteroid

ARM Proposed Mission

Two Robotic Capture Options are being Studied:





- More information is available at:

http://www.nasa.gov/mission_pages/asteroids/initiative/

Target NEA & Boulder Size/Mass Comparison

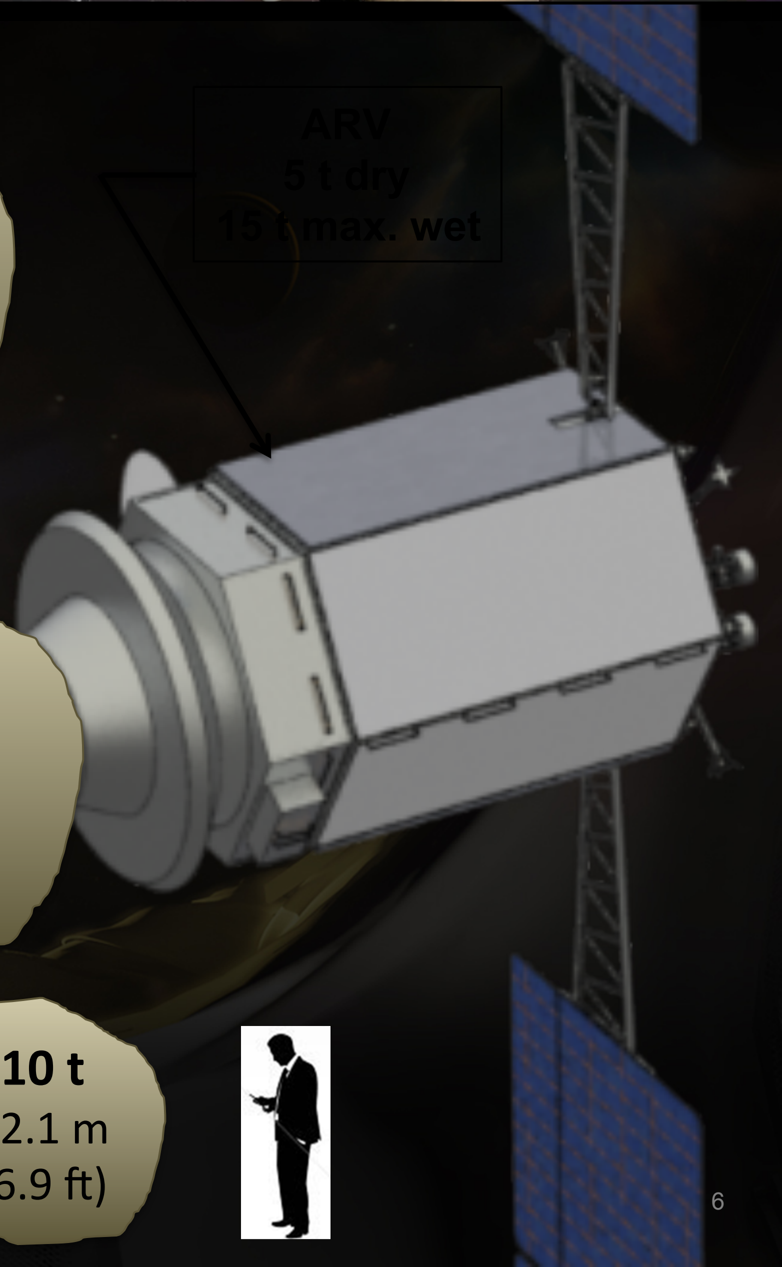
NEA & boulder mass estimates assume density of 2 g/cm^3

ARV
5 t dry
15 t max. wet

70 t
~4.2 m
(13.8 ft)

100 m NEA
~1,000,000 t

40 t
~3.4 m
(11.2 ft)



10 t
~2.1 m
(6.9 ft)

Candidate Asteroids for Mission Design

- **Assuming mid-2019 nominal launch**

Asteroid	Asteroid Mass Est.	Asteroid V-infinity	Earth Return Date	Crew Accessible	Notes
2009 BD*	30-145 t (returnable)	1.2 km/s	Jun 2023	Mar 2024 or earlier	Valid mission candidate, rotation period > 2 hrs, Spitzer-based upper bound on mass
2011 MD*	TBD (max 620 t)**	1.0 km/s	Jul 2024	Aug 2025	Spitzer obs. successful final characterization results pending Rotation period 0.2 hrs
2014 BA3	TBD (max 500 t)**	1.8 km/s	Jan 2024	Early 2025	Discovered Jan 2014, not detected by Radar Optical characterization pending
2013 EC20	4-43 t (returnable)	2.6 km/s	Sept 2024	Late 2025	Discovered March 2013, Radar characterized rotation period ~ 2 min 2024 return requires DIV H or FH launch 2020 return possible with Feb 2018 launch
2008 HU4	TBD (max 700 t)**	0.5 km/s	Apr 2026	Mid 2027	Close Earth flyby in April 2016

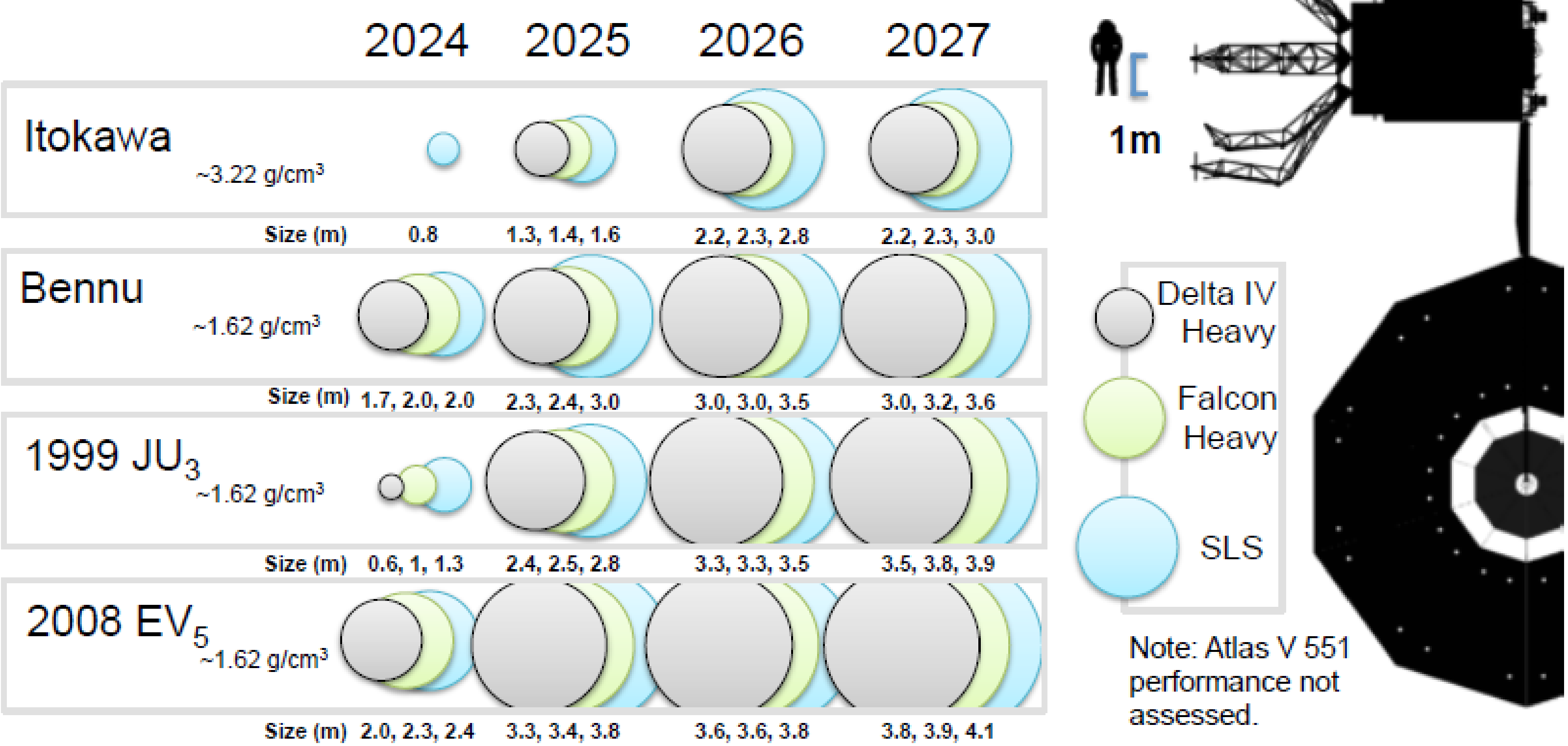
* High-fidelity trajectory analysis performed for 2009 BD and 2011 MD

** Max returnable mass using a Delta IV Heavy or Falcon Heavy

Candidate Target Boulder Return Sizes

Launch no earlier than June 2019

Crew Availability in stable LDRO in February - May of:



Robotic Boulder Capture Option has a set of candidates that are robust to changes in return dates.

Masses and additional data for June 2020 and June 2021 launches in backup

NEA Resources for ISRU

Major resources/uses from NEA material:

- **Regolith**:
  - Oxygen from mineral oxides and
  - Metals: iron, nickel, PGMs
- **Water** and other volatiles bound in regolith
- Bulk material for radiation shielding & construction

Meteorite Taxonomy

Stones	96%	Silicate dominated
Chondrites	88%	Primitive undifferentiated; iron oxidized 30 – 100%
Achondrites	8%	Silicate rich igneous mat'l – 99% silicates and oxides
Strony-Irons	1%	50% ferrous metal alloys/ 50% silicates (mostly olivine)
Irons	3%	99% Metallic Fe-Ni-Co alloys

At least 1/5th of NEAs are volatile-rich.
Almost all others are metal rich

Ordinary Chondrites 87%
(H, L, LL)
FeO:Si = 0.1 to 0.5
Fe:Si = 0.5 to 0.8

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Trioilite - FeS

Source metals

Carbonaceous Chondrites 9%
(C Type: C1I, C2M, CO, CV)
Highly oxidized w/ little or no free metal
Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles

Enstatite Chondrites 4%
(Eh, EL)
Highly reduced; silicates contain almost no FeO
60 to 80% silicates; Enstatite & Na-rich plagioclase
20 to 25% Fe-Ni
Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen

ARM Targets

- Itokawa: S-type, stony
- Bennu, 1999JU3, 2008EV5: Carbonaceous chondrites, CI or CM meteorite typing, 10-20% water
- 2011UW158, 2009DL46: insufficient data to classify
- Other ARM targets: insufficient data to classify

- 2009 BD: 5-7 meters – too small to characterize
- The search is continuing…..

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ISRU Task: Background & Purpose

- Develop operations concepts development for:

   1. Evolutionary ISRU <u>Technology Demonstrations</u>
   2. Translunar ISRU operations for <u>forward implementation</u> at Mars

   - Both leveraging ISS, Orion, Asteroid Redirect Vehicle (ARV), other augmentation elements, and possibly lunar assets.

- Purpose of this task is to inform the overall architecture and campaign development, functionality, technology, and potential ISS and analog activities.

- Cis-lunar space is a useful label for "the volume between geostationary orbit and the moon's orbit".
- Beyond cis-lunar space lies translunar space.

- Translunar in this context is shorthand for “Earth-Moon System” which includes cis-lunar and translunar space.

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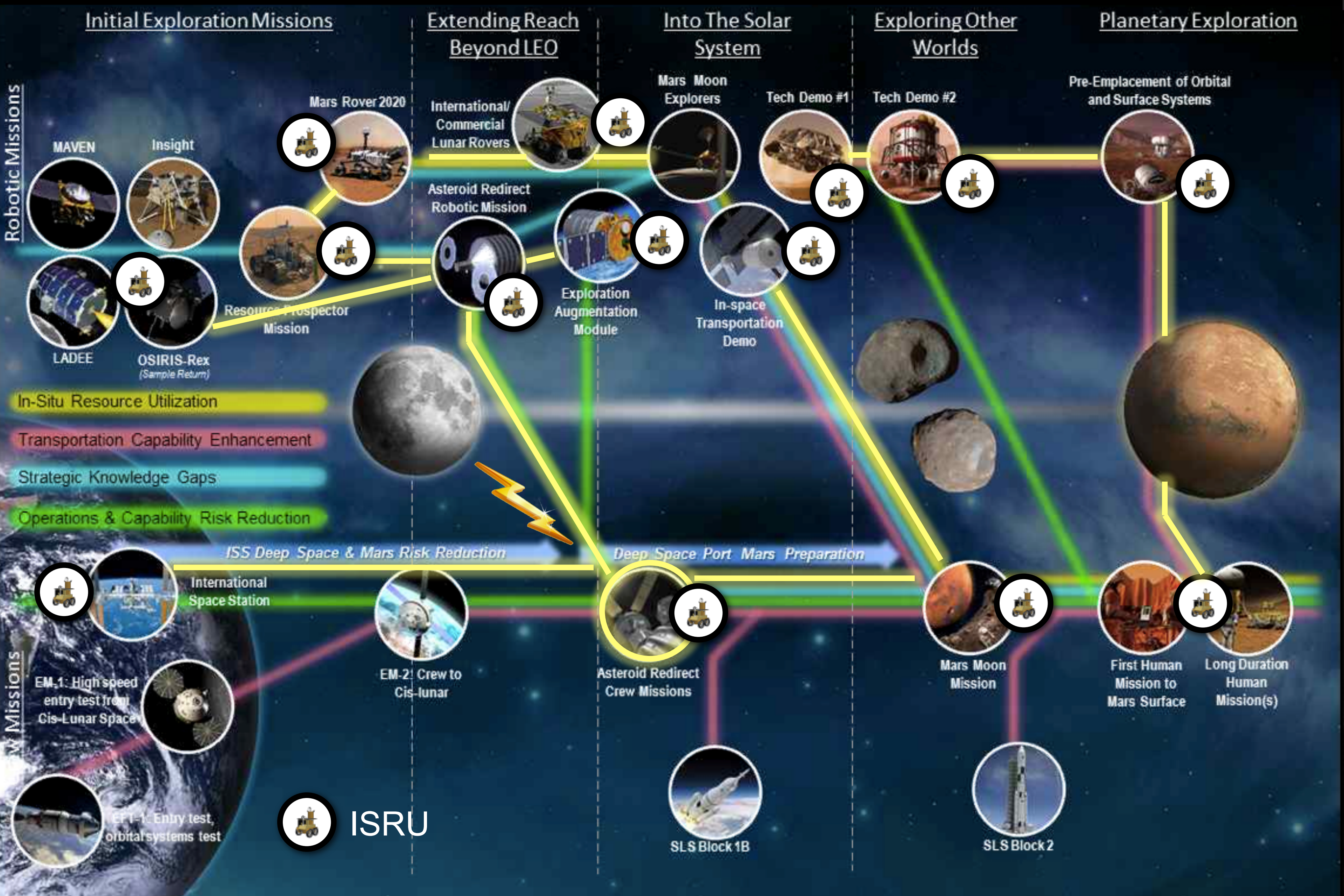
ISRU Evolution in an Evolvable Mars Campaign

- ISS Experimental Campaign, e.g.:
  - Granular material transfers / handling in micro-g
  - Material control in micro-g (gas/liquid, solid/melt, gas/solid, liquid /solid)
  - Teleoperations of ISRU processors
  - In-vaccuo operations of ISRU elements (external carrier platform)

- Lunar
  - Lunar surface early sample prospectors: RPM-1 (RESOLVE); RPM-2
  - Lunar surface asset deployment for large-scale resource discovery (tech demos)
  - Resource extraction in partial gravity (practice for Mars gravity)
  - ISRU assets Low Latency Teleoperated (LLT) from ARM Stack at LDRO (practice for Phobos to Mars teleops)

- Returned NEA at LDRO
  - New material exploration – prospecting, identification, scale issues
  - Micro-g ISRU operations (practice for Phobos)
  - ISRU teleops (LLT)
  - Crew involvement in ISRU (practice for Phobos, Mars)
  - Repeated / large volume resource transfer and processing
  - Multiple ISRU assets teleoperations (LLT)

Evolvable Mars Campaign – Notional ISRU Integration



Possible Scenario Themes

1. Telerobotics Assets performing ISRU tasks on captured asteroid
   - Deployed and operated within vehicle stack near Asteroid (Practice for Phobos)
   - Enables crew intervention on ISRU systems and telerobotics maintenance (Practice for Mars ISRU and teleoperations from Mars orbit)
   - Tech Demo location: ***Asteroid***

2. Telerobotics Assets performing ISRU tasks on the lunar surface
   - Potential RPM-2 controlled from ISS or ARM vehicle stack as an ISRU precursor (RPM 1 will be controlled from Earth - 2018)
   - Resource prospecting technology demos for space mining (Practice for Mars)
   - Deployed and operated by crew at ARM in LDRO (Practice for Phobos/Mars)
   - ISRU tasks being performed in partial gravity (Practice for Mars)- Tech Demo location: ***Moon***

3. Other ISRU activities in translunar space (ARM Stack external carrier platform)
   - Conditioning/storing extracted resources (water, oxygen, volatiles)
   - Processed material characterization & utilization (partially reduced minerals, glass, fiber-pulling)
   - Tech Demo location: ***ARM vehicle stack on a carrier platform***

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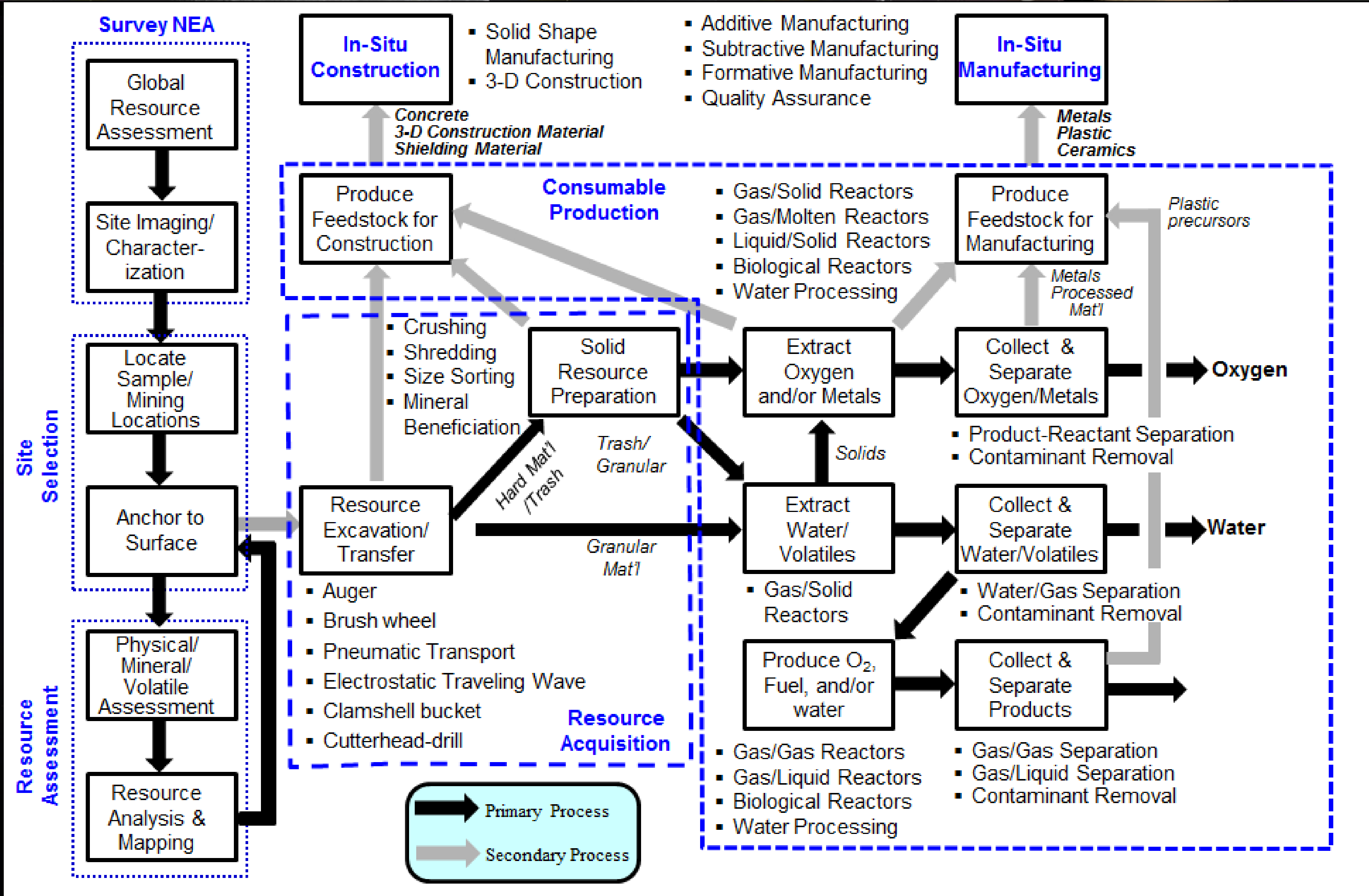
NEA ISRU Capability-Function Flow Chart



Goals & Objectives: In Situ Resource Utilization

G2.6.1: Extraterrestrial mineral resources → Water and volatiles

G2.6.2: Extraterrestrial mineral resources → Oxygen and metals

G2.6.3: Extraterrestrial mineral resources → Non-extractive regolith and rock processes

G2.6.4: Mars atmosphere → oxygen and/or fuel

G2.6.5: Crew trash and waste → Consumables and propellant

G2.6.6: Expended hardware → Useful products

G2.8: Utilization of ISRU propellants in translunar space

G6.3a: Commercial launch and cargo to deliver ISRU demo

G6.3b: Government purchase of commercial ISRU propellant

G7.1: Public engagement in ISRU testing

M4.2: Characterize water on Mars for exploration

Asteroid and Lunar Surface

Asteroid

Mars

Other

Objectives and Activities: Near-Earth Asteroid ISRU

- **G2.6.1: Extraterrestrial mineral resources → Water and volatiles**
  - Determine availability of water and volatiles in asteroidal material
  - Acquire, prepare, and process samples
  - Store acquired water and/or volatiles for future analysis and use
- **G2.6.2: Extraterrestrial mineral resources → Oxygen and metals**
  - Determine mineralogy of asteroidal material
  - Acquire, prepare, and process samples
  - Store acquired oxygen and/or metals for future analysis and use
- **G2.6.3: Extraterrestrial mineral resources → Unreacted rock/regolith**
  - Acquire samples
  - Perform non-reacting processes to demonstrate use of unreacted material
- **G2.8: Utilization of ISRU propellants in translunar space**
  - Transfer ISRU products from process nodes to use nodes
  - Utilize ISRU products as propellant

Task 11A Top Level Functions (ISRU) at Returned Asteroid in Translunar Space

- Perform detailed survey of asteroid before collection or in LDRO (scale or scope of prospecting will drive the required technologies)
- Select location for analysis/processing
- Deploy Resource Prospector/ISRU Demo to selected site
- Acquire samples of regolith/soil
- Prepare sample for processing
- Process resources
- Dispose/recycle waste products
- Store products: water/volatiles/oxygen/metals
- Store unchanged regolith

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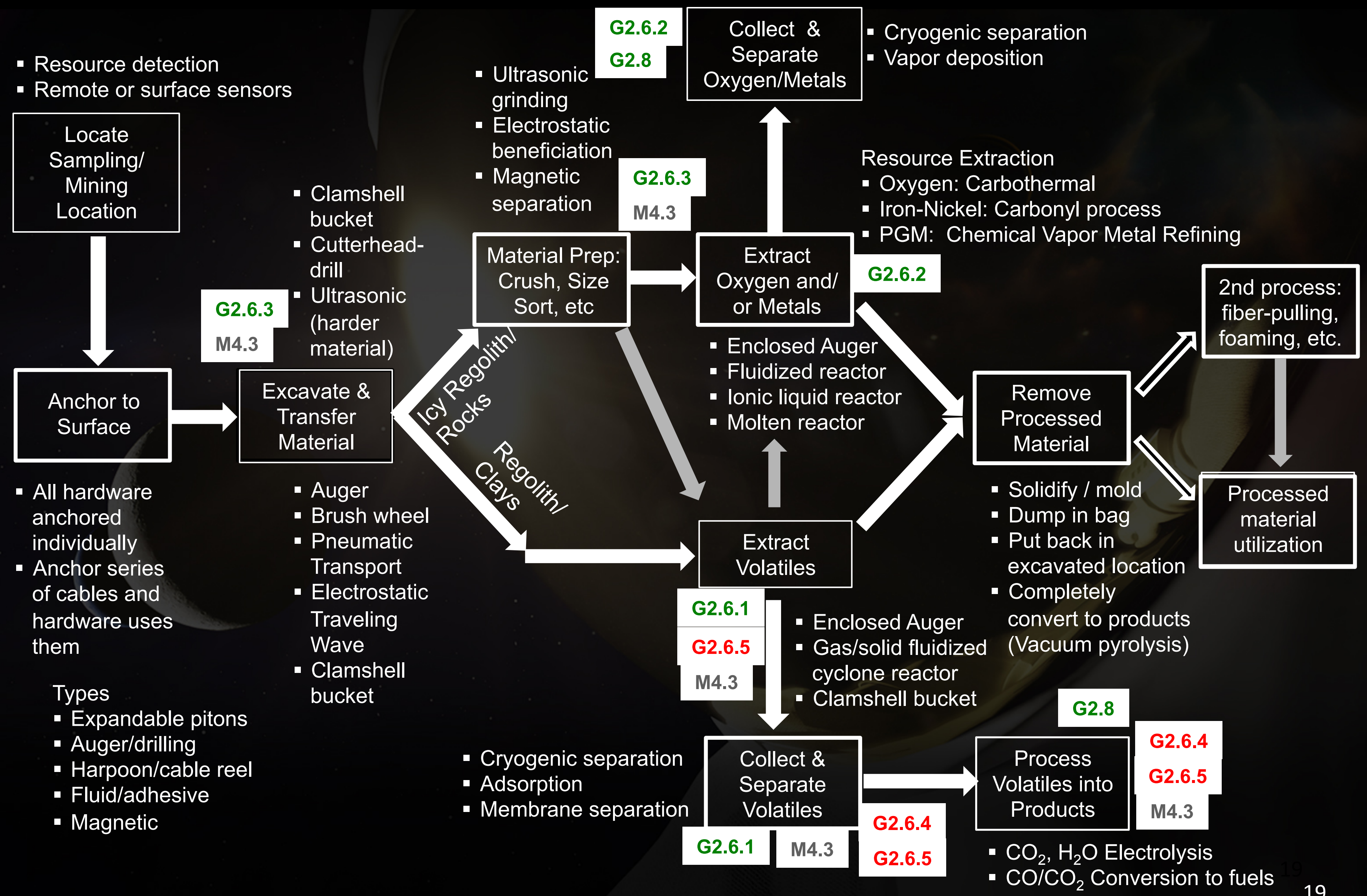
Functional Decomposition of Resource Prospecting & ISRU (Translunar – Returned Asteroid)



Translunar ISRU Design Space – Returned Asteroid

Trades — Identified Options · Notional Implementation · Other Options

Asset Control	Crew Elements	Stack Elements	ISRU Elements	Surface Ops	Sample Transfer	Off-Surface ISRU Processes
From Lunar Orbit	EAM + Orion	EAM external carrier platform	Prospecting/ detection probes	Subsurface Resource mapping	Direct pneumatic piping to ISRU process	Regolith transfer into reactor
From Earth	Orion Only	ARRMV	Excavators	Identify sampling/ mining locations	EVA Assisted Transfer	Regolith/Rock crushing - sizing
…	…	ARRMV-alt	Rovers/ Walkers	In situ sample Analysis	Free flying regolith carriers	Water/Volatiles thermal extraction
…	…	…	Sample carriers	Acquire asteroid material	Augering	Mineral oxide reduction
…	…	…	Furnace	Extraction	Tethered or rail-guided	Product characterization
			Molecular & elemental analyzers			
			Resource storage			

Internal EVA?

ARRMV: Asteroid Redirect & Return Mission Vehicle
EAM: Exploration Augmentation Module
LAV: Lunar Ascent Vehicle
EVA: Extra-Vehicular Activity
IVA: Intra-Vehicular Activity

Potential Extracted Resources from an Asteroid

- **Consumables**
  - Propellants: transportation, EAM station keeping and EVA SAFER
  - Breathing Air : ECLSS makeup
  - Breathing Air : EVA PLSS supply
  - Water : Human consumption
  - Water: Crew Hygiene
  - Water: Grow Plants for life support loop closure and/or food

- **Radiation Protection**
  - Water: hydrogen shielding
  - Organics: hydrocarbons
  - Bagged regolith

- **Manufacturing**
  - Metals: Parts manufacture for logistics reduction
  - Regolith: structures, parts

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µ-g/Space Mining Issues and Challenges

- Rock fracturing imparts velocity
- Inertia still needs to be managed in zero-G /micro-G
- Anchoring
  - Low material strength is good for mining but bad for anchoring
  - Applying reactive force in other direction during anchoring
- Micro-gravity processing and separation
  - Solid transport and holding bin, size sorting, beneficiation, and crushing operations are normally gravity dependent
  - No gravity for solid/gas separation during extraction processing
  - Material clogging
- Regolith - Friction, cohesion, and electrostatic forces may dominate in micro-g
- Dust/fine particles
  - Impact on actuators, augers, seals, etc
  - Dust obscures camera views; situational awareness and control degraded
  - Changing thermal properties of hardware and radiators
- Radiation environment
- Material – Process feedstock
  - Wide variation of physical and mineral properties possible
  - Unknown process volatile and mineral contaminants
- Automation and health management; remote operations with long-time delays in communication

➢ To spin or not to spin?: Rotating asteroid vs de-spinning. Spinning NEO:
  - Will provide centrifugal force for movement/debris capture
  - Will cause variations in thermal environment for hardware
  - Will make solar power systems difficult to design/operate; cycling of solar thermal processing

Conclusions

- **State-of-knowledge and assumptions defining the nature of materials expected for each NEA candidate are required**
  - Drives selection of processing technologies for ConOps and estimates
  - Highlights common characteristics & difference with Phobos for carry-forward ISRU technology maturation to Mars missions
- **Micro-G ISRU technology needs to be developed**
  - Currently at very low Technology Readiness Level (TRL)
  - Pre-cursor experiments & investigations will be required at the International Space Station (ISS)
- **ARM ISRU capabilities may enhance a journey to Mars and Low Latency Lunar Tele-Operations from the LDRO**
- **ARM ISRU has potential to feed forward to Mars orbits if Phobos/Deimos are considered in the mission architecture**