A Systems of Systems Methodology for Conceptual Studies of In-Situ Resource Utilization for Near Earth Object Applications

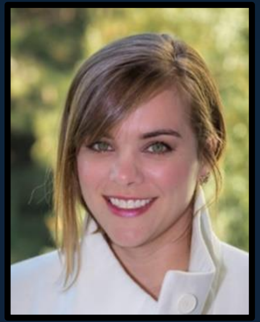
Defense Slides (updated with extra results)

Thursday, 2nd July 2020

Christopher Kitson

Masters' Thesis Committee

Advisors



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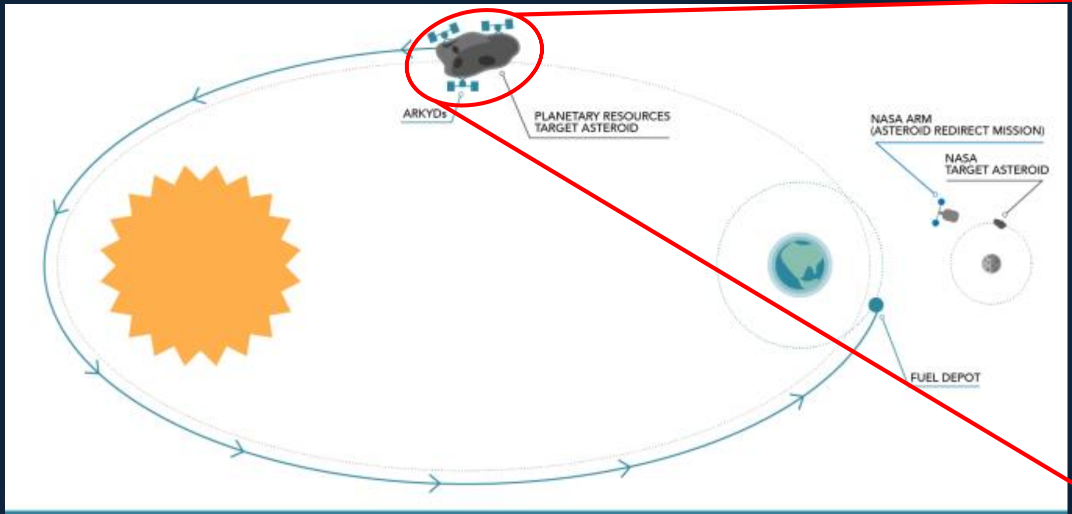
Focus of Research

Create a method to explore the design space of industrial activity in outer space around asteroids and to better compare concepts.

Case study is to examine a pilot plant deployed to an asteroid, which is designed to produce enough propellant to return a given mass to Earth orbit.



Resource extraction happens within the asteroid's orbit around the Sun.
Then, the refined resources are delivered to their point of need, such as high-Earth orbit.

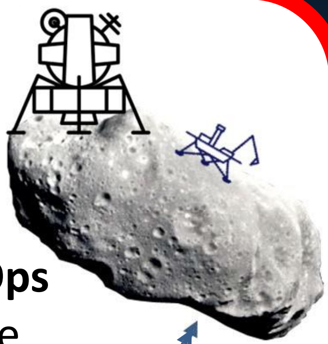
HoneyBee Robotics Spider

Planetary Resources, 2015. "Safe and Efficient Asteroid Mining".
Zacny, Kris 2017 "Asteroid ISRU" SBAG, Tuscon, AZ,

Scope: Asteroid Proximity

- Introduction
- Motivation
- Methodology
- Implementation
- Conclusions

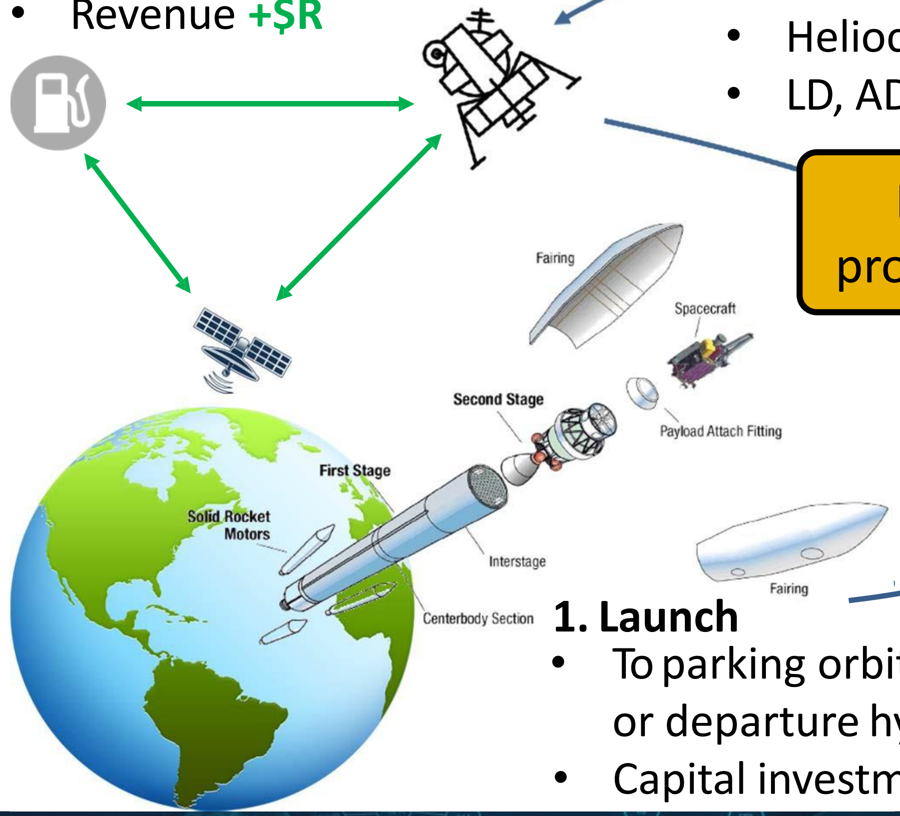
Focus



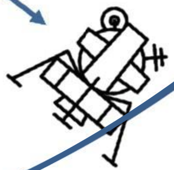
3. Mining Ops
- Stay-time
- Resource Mass

5. Delivery
- Depot/Customer
- Refuel for next trip
- Revenue **+$R**

4. Asteroid to Earth
- Heliocentric transfer
- LD, AD, TOF, ΔV



Examining subset of a larger problem; not all variables needed



2. Earth to Asteroid
- Heliocentric transfer
- LD, AD, TOF, ΔV

1. Launch
- To parking orbit (IMLEO) or departure hyperbola
- Capital investment **-C_0$**

Dorrington, Scott. 2017 “Asteroid Mining Logistics”. Presented at the 2017 Off Earth Mining Forum

Framing Questions

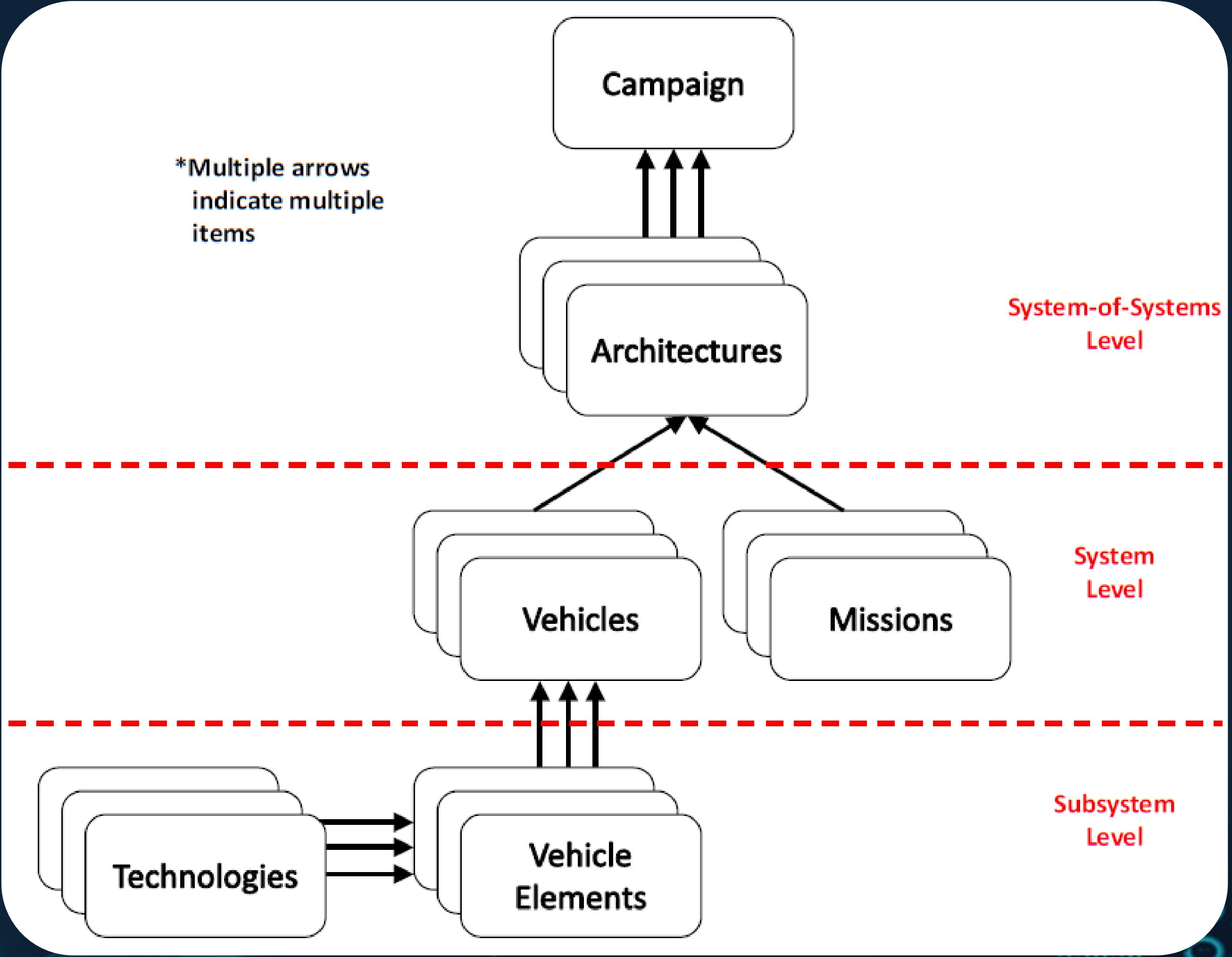
Why are Near Earth Objects (NEO) of interest?

Why develop better models for In-Situ Resource Utilization (ISRU)?

Why is a Systems of Systems (SoS) mindset beneficial?

A Hierarchy of Design Levels

- Systems of Systems (SoS) are comprised of systems, where the whole is greater than the sum of its parts
- SoS have:
  - Emergent capabilities beyond constituents
  - New functional niches for systems or subsystems
- Technologies must be rolled-up to ascertain impacts in SoS context
- 'Concept' means proposed architecture in this work



Trent, D. J. (2011). *Integrated Architecture Analysis and Technology Evaluation For System of Systems Modeled At The Subsystem Level* [Dissertation, Georgia Institute of Technology].

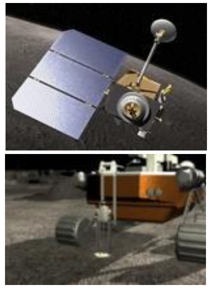
In-Situ Resource Utilization (ISRU)

Introduction
Motivation
Background
Existing Gaps
Methodology
Implementation
Conclusions

ISRU is broadly defined, encompassing nearly all industrial activity in space.

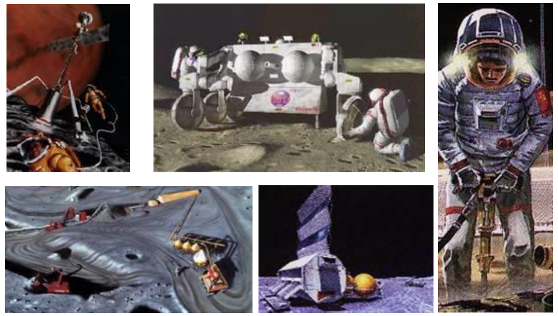
A reduction in payload mass is sought, by producing on-site instead of bringing

Resource Assessment (Prospecting)



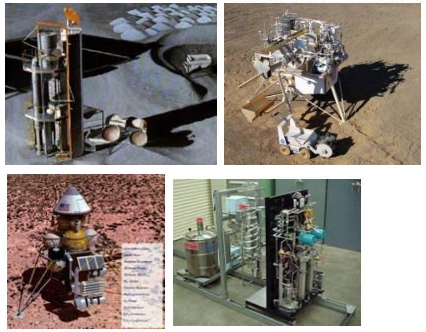
Assessment of physical, mineral/ chemical, and volatile/ water resources, terrain, geology, and environment (orbital and local)

Resource Acquisition



Extraction, excavation, transfer, and preparation before processing

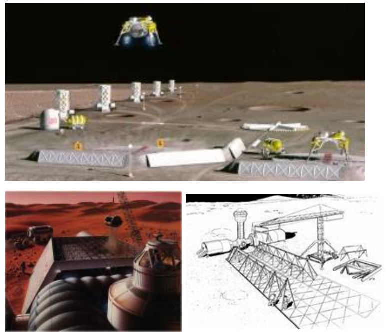
Resource Processing/ Consumable Production



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

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

In-Situ Construction



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

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

In-Situ Manufacturing

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

In-Situ Energy

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

➢Solar arrays, thermal wadis, chemical batteries, etc.

In-Situ Resource Utilization (ISRU)

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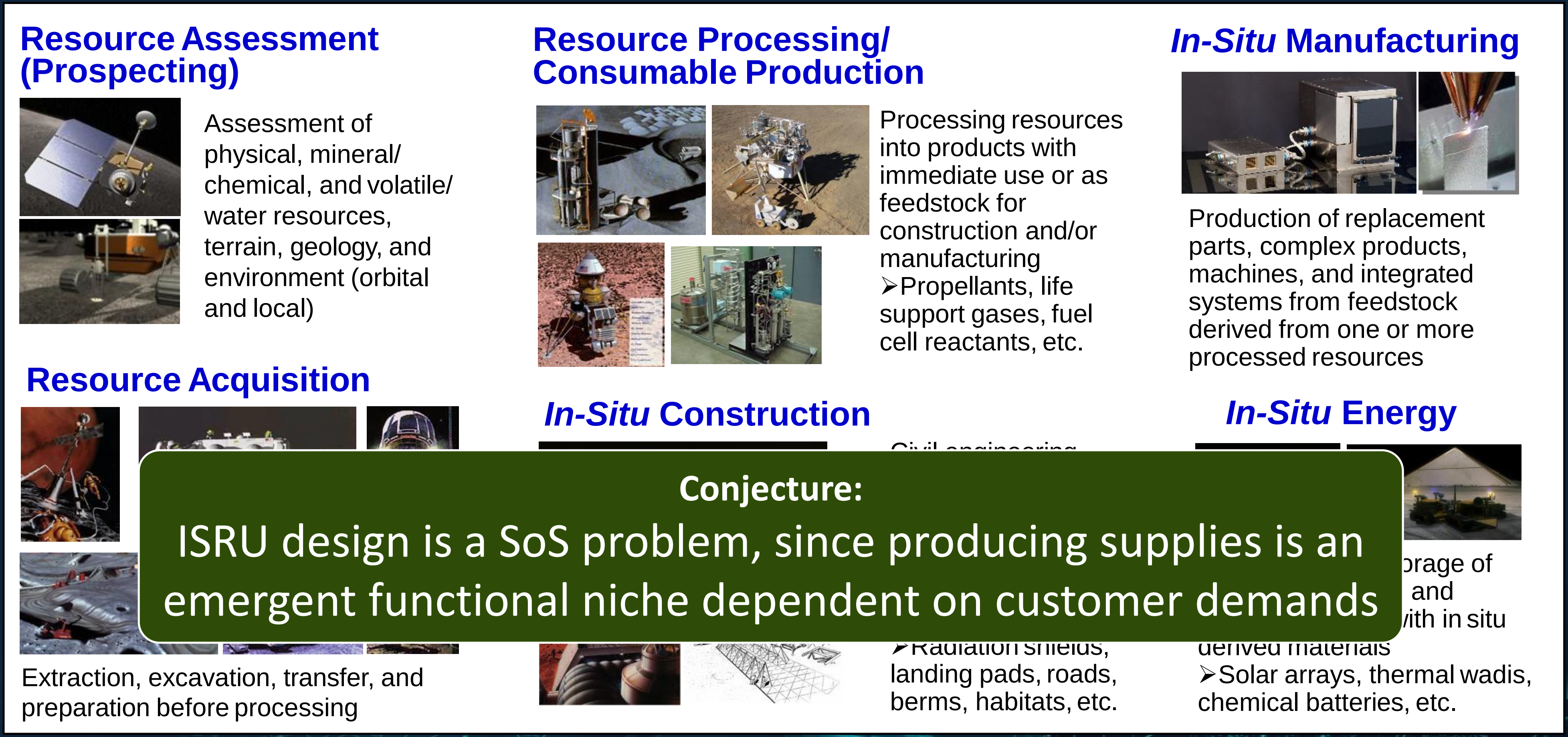
A reduction in payload mass is sought, by producing on-site instead of bringing



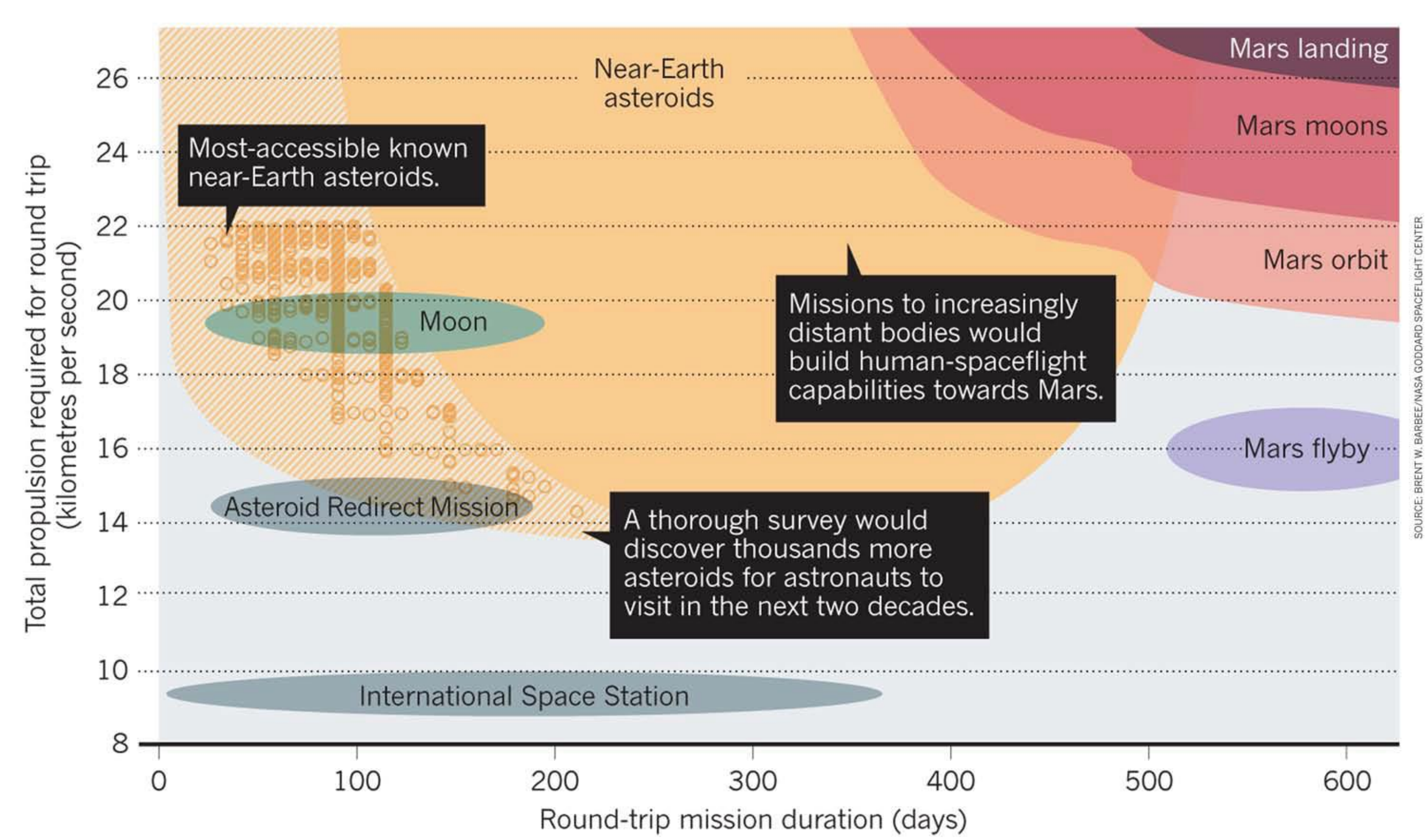
Conjecture:

ISRU design is a SoS problem, since producing supplies is an emergent functional niche dependent on customer demands

Linne et al., 2016. “Overview of Proposed ISRU Technology Development”.

Spaceflight Destinations

Round Trip Δv: (Earth/KSC -> LEO -> Destination -> LEO -> Earth)

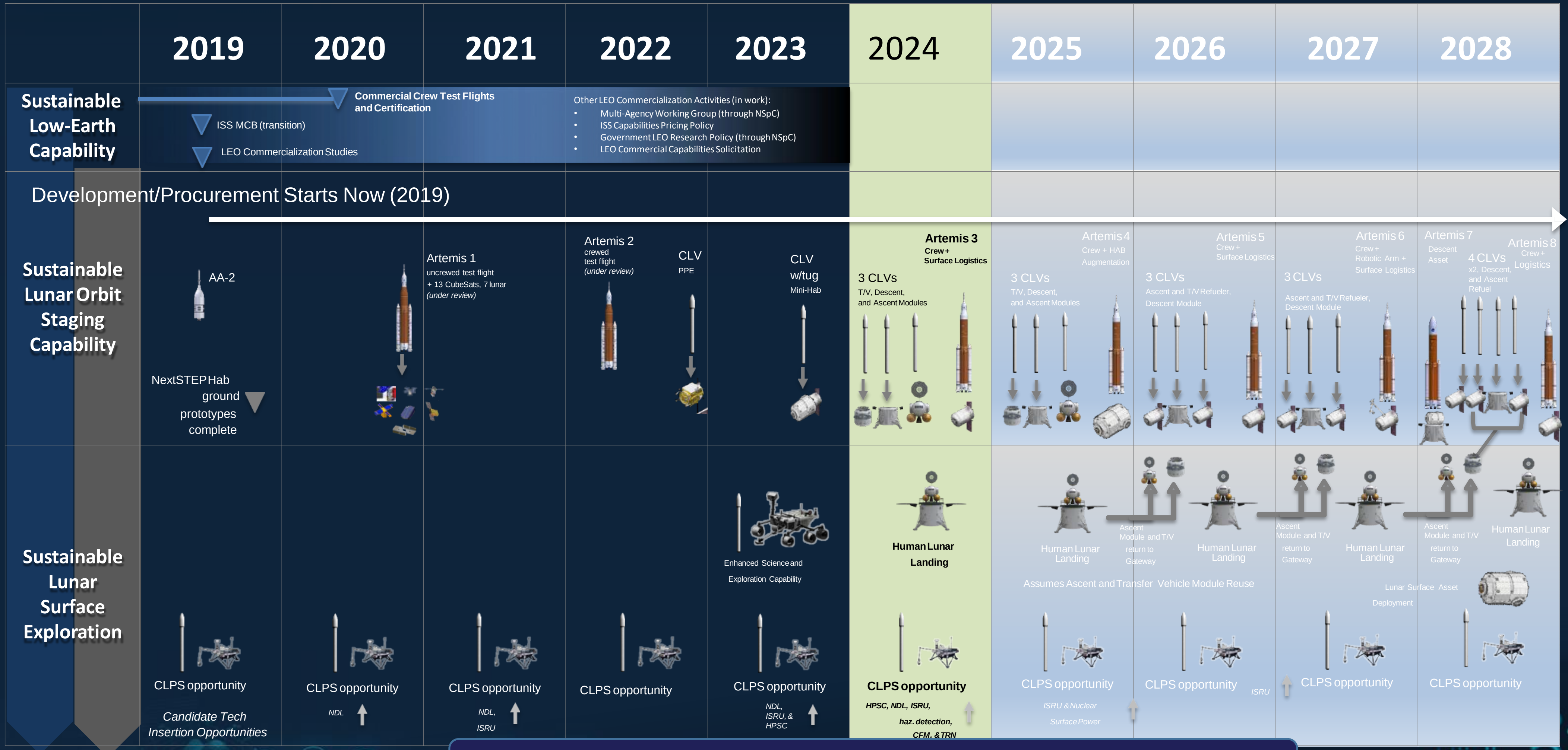


Near Earth Objects (NEO):

- Asteroids & Comets
- Orbits pass close to Earth's
- Numerous options, with large variability

Binzel, Richard, 2014. "Human Spaceflight: Find Asteroids to Get to Mars". Nature 514(7524): 559–561.

NASA Artemis – 'Sustainability' Implies ISRU



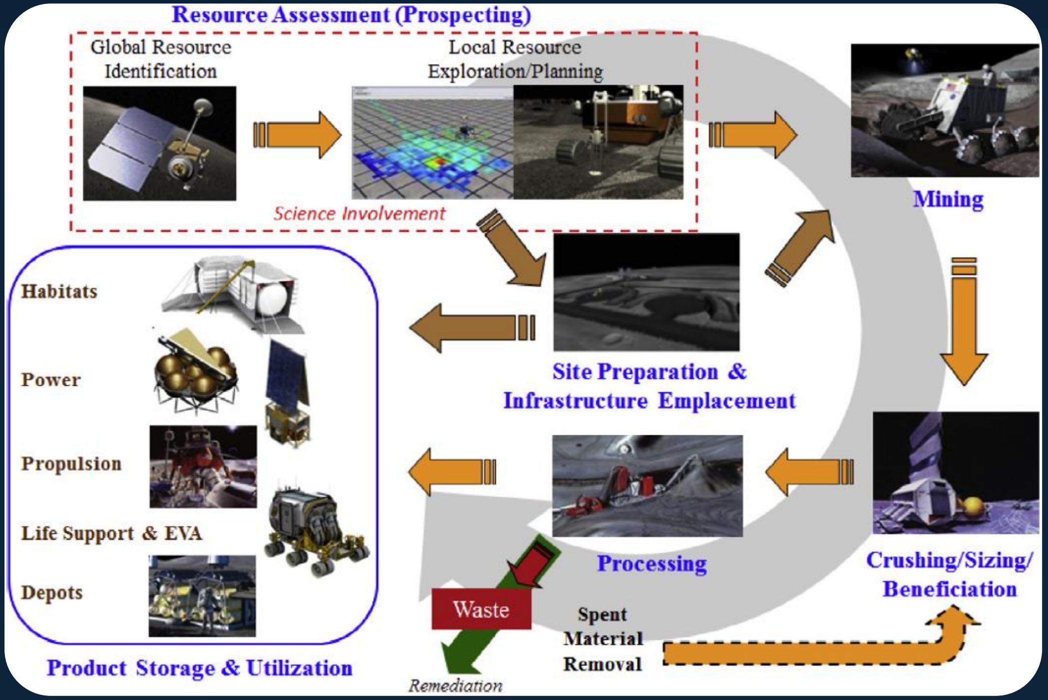
ISRU ISRU ISRU ISRU ISRU

Christopher Kitson

NASA. (2019, 6th June). *Forward to the Moon: NASA's Strategic Plan for Lunar Exploration*. Retrieved From: https://www.nasa.gov/specials/moon2mars/#how

ISRU: Failure to Launch

- Mismatch between recognized potential and use in field
  - Desired capability since 1960's
  - ISS ECLSS closest thing flown
  - Analog prototype ground tests perceived as insufficient risk reduction for flight mission use
- ISRU research focuses on crew, despite lowest failure tolerance



- ISRU does not operate in isolation, it needs a customer: *'Network utility'* for space *'platform'* in need of a *'killer app'* [1]
  - Crew consumables (e.g. oxygen to breathe)
  - Rocket propellant (e.g. hydrogen-oxygen or 'hydrolox')

[1] Sercel, 2018 "Thoughts about Asteroid Mining,"
[2] Sanders and Larson, 2015, doi: 10.1016/j.asr.2014.12.024.

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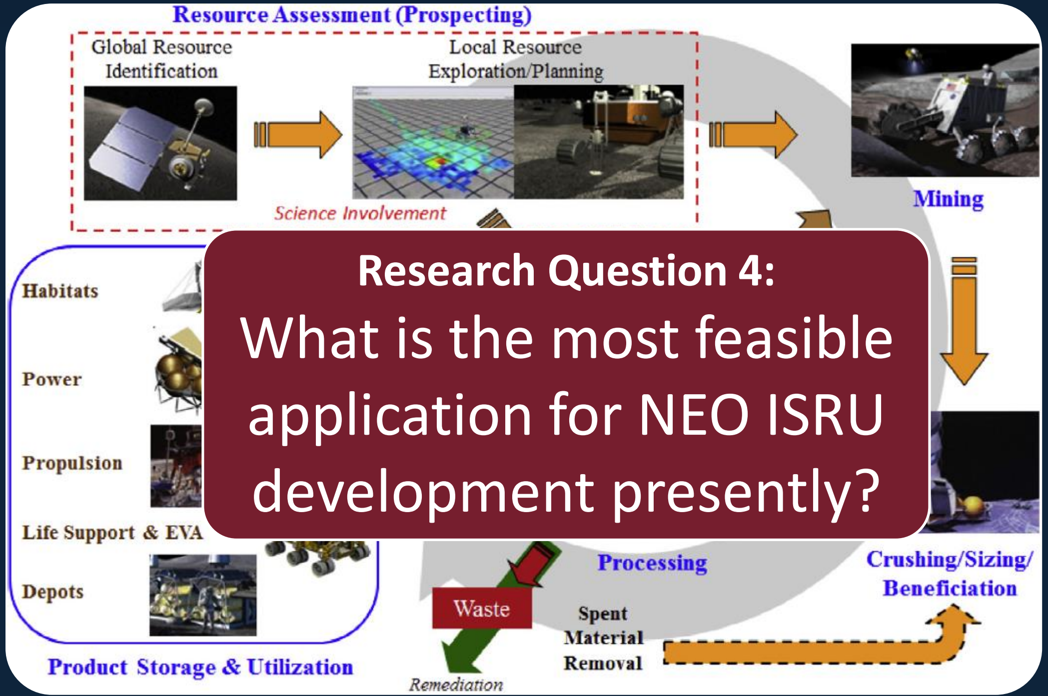

Research Question 4:
What is the most feasible application for NEO ISRU development presently?

- ISRU does not operate in isolation, it needs a customer: *'Network utility'* for space *'platform'* in need of a *'killer app'* [1]
  - Crew consumables (e.g. oxygen to breathe)
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Contrasting Destinations

Category	Mars	Luna	NEO	
Δv: Surface from LEO	≥ 12.5 km/s	≥ 9 km/s	**≥ 4.5 km/s**	[1]
Arrival	Entry, Descent, & Landing	**Descent & Landing**	Rendezvous with uncooperative target	
Past Mission Failures	Many	Occasional	**Few**	
Weather	Dust storms, Abrasion	Static discharge/cling Abrasion, Long nights	**Static discharge/cling, Abrasion, space weather**	
Planetary Protection	IV; V (restricted)	II; V (unrestricted)	**I or II; V (unrestricted)**	
Landing Sites Considered	1 planet Mars ~50 sites (Curiosity)	1 moon of Earth ~5 sites (Luna-Glob)	**17,607 asteroids (2018) ~4 sites each (OSIRIS-REx)**	[2]
Water Availability	Subsurface ice (widely distributed)	Pole crater ice (site specific)	**Hydrates & buried ice (target dependent)**	

Conjecture:
NEO offer better conditions for developing ISRU capabilities than Luna or Mars

[1] Barbee, B. W. (2015, January 7). *Accessible Near-Earth Objects*
[2] L. A. M. Benner, “Near-Earth Asteroid Delta-V for Spacecraft Rendezvous,” Jan. 26, 2018.

Gaps In Existing Models of ISRU

- Unsupported Assumptions
  - Scaling laws: often a-priori assumptions in space logistics studies
  - Errors of omission: missing functionality (esp. thermal) in concepts
  - Microgravity: forget lack/reduced natural resorting forces, buoyancy, etc.
- Point Designs
  - One-off efforts common
  - "Technology is trying to drive mine planning" [1]
- Difficulty of Comparison
  - Few shared metrics
  - Wildly varying levels of detail included within same concept's systems

Existing Concept	Missing Func. [#]	Specified Func. [%]	Primary Source
Honey Bee APIS (TransAstra Corp.)	4	91%	Sercel, 2016
Spider (HoneyBee Robotics)	4	91%	Zacny et al., 2016
Robotic Asteroid Prospect (Astrotecture et al.)	6	86%	Cohen et al., 2013
Cornucopia (Star Technology & Research)	6	86%	Buet et al., 2013
Hein et al. (Initiative for Interstellar Studies)	10	77%	Hein et al., 2019
RockBreaker (Georgia Tech ASDL)	12	72%	Vanmali et al., 2005
Konstantin & Mules (Catalyst Corporation)	13	70%	Daniel Suarez, 2019
O'Leary et al. (NASA Ames)	14	67%	Billingham et al., 1979
Surculus Astrum (Univ. of Washington)	18	58%	Andrews et al., 2015
Kuck 'Mosquito'	19	56%	Kuck, 1997
(Planetary Resources)	19	56%	US 9266627 B1 (2016)
CAVoR (Pioneer Astronautics)	21	51%	US 20180194626 A1
Sonter (Asteroid Mining Group)	21	51%	Sonter, 1997
Gertsch et al. 'Non-Cohesive' (Missouri S&T)	24	44%	Gertsch et al., 1997
(Deep Space Industries)	26	40%	Lewis & Gump, 2015
Nallapu et al. (Arizona State)	26	40%	Nallapu et al., 2016
Sommariva (Meta Consulting)	30	30%	Sommariva, 2015
Gertsch et al. 'Cohesive' (Missouri S&T)	31	28%	Gertsch et al., 1997
Kargel (USGS)	33	23%	Kargel, 1994
Benaroya (Rutgers University)	34	21%	Benaroya, 2013
Mean	18.6	57%	43 subsystem functions
Standard Deviation	9.7	23%	20 concepts

[1] Neal et al. 2019 "Lunar ISRU 2019: Workshop Report".

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Cornu[illegible]			[illegible]2013
Hein et[illegible]			[illegible]019
Ro[illegible]			[illegible], 2005
Konsta[illegible]			[illegible], 2019
			[illegible]l., 1979
Surcu[illegible]			[illegible], 2015
			[illegible]7
			[illegible] (2016)
			[illegible]26 A1
S[illegible]			[illegible]97
Gertsch[illegible]			[illegible] 1997
			[illegible], 2015
			[illegible] 2016
S[illegible]			[illegible]2015
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Research Objective:
A methodology will be developed to compare on equal footing In-Situ Resource Utilization (ISRU) System of System (SoS) concepts involving Near Earth Objects (NEOs).

[1] Neal et al. 2019 "Lunar ISRU 2019: Workshop Report".

Preforming Systematic Comparisons

Research Question 1:
How can comparisons between In-Situ Resource Utilization (ISRU) System of Systems (SoS) be done systematically at the conceptual level?

- Design – specifications for how to accomplish a goal
  - Normally describes a system, or collection of them (System of Systems)
  - Goal can be a function, purpose, task, or mission
- Requirements – constraints placed upon a design
  - Limits the options considered within the design space
  - Stakeholders impose requirements to align the design with their aims

Conjecture:
Design aspects can be categorized as either qualitative or quantitative

Morphological Matrix of Alternatives

- Qualitative requirements can be represented by discerning amongst alternatives that fulfil the same function
- These design alternatives are tabulated by characteristic in a **morphological matrix**
- A **concept** is a set of morphological options, where one option from each row is selected from the matrix
- Trade studies are enabled by definition of the morphological options within the design space

	Characteristics \ Alternatives	1	2	3	4
Config	Vehicle	Wing & Tail	Wing & Canard	Wing, Tail & Canard	Wing
Config	Fuselage	Cylindrical	Oval	None	
Config	Pilot Visibility	Synthetic Vision	Conventional		
Mission	Range (nmi)	3000	3500	4000	
Mission	Passengers	100	150	200	
Mission	Mach Number	0.8	0.83	0.85	0.9
Prop	Type	Turbofan	AST Engine	IHPTET	
Prop	Combustor	Conventional	RQL	LPP	
Control	Static Stability	Stable	Unstable	Relaxed	
Control	Gust control	Conventional	Unloaded		
Aero	Low Speed	Conventional Flaps	Conventional Flaps & Slots	C C	
Aero	High Speed	Conventional	LFC	NLFC	HLFC
Struct	Wing	Aluminum	Titanium	Composite	
Struct	Fuselage	Aluminum	Titanium	Composite	

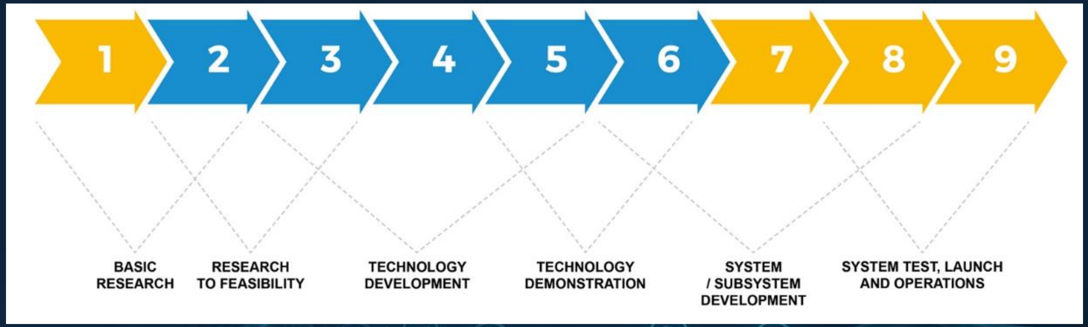
Selection of an aircraft concept from a morphological matrix (Mavris & Kirby, 1999)

Mavris, D. N., & Kirby, M. R. (1999, May 24). *Technology Identification, Evaluation, And Selection For Commercial Transport Aircraft*. 14. San Jose, California: Society of Allied Weight Engineers.

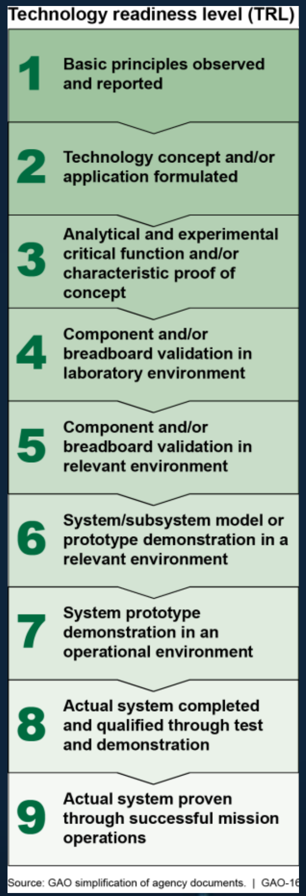
Technology Readiness Levels

- Introduction
- Motivation
- Methodology
  - Qualitative
  - Quantitative
  - Application
- Implementation
- Conclusions

- Technology Readiness Levels (TRL) are used to assess the maturity of design alternatives
- Development risk can be quantified using TRLs; higher TRLs have lower dev. risk
- The TRL of a system is the minimum of its components' TRL



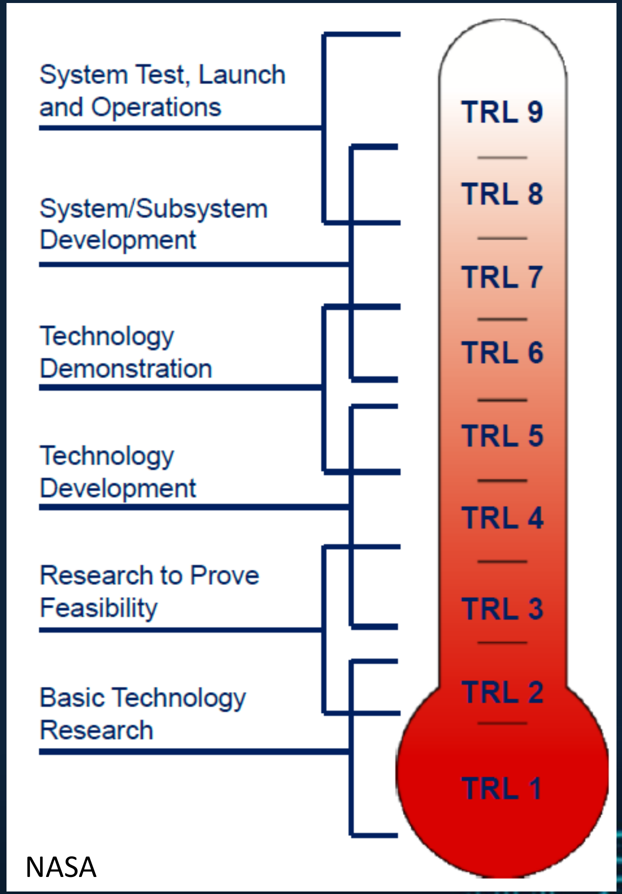
Game Changers



Technology readiness level (TRL)	
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations

Source: GAO simplification of agency documents. | GAO-16

GAO



NASA

Hirshorn, S., & Jefferies, S. (2016). *Final Report of the NASA Technology Readiness Assessment (TRA) Study Team* (p. 63).
Persons, T. M., & Sullivan, M. J. (2016). *Technology Readiness Assessment Guide* (No. GAO-16-410G).

Facilitating Qualitative Comparisons

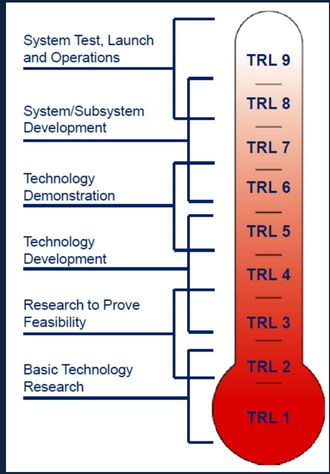
Research Question 2:
What is the most feasible set of morphological options for an In-Situ Propellant Production (ISPP) System of Systems (SoS) using Near Earth Object (NEO) resources based upon technological readiness alone?

	Characteristics \ Alternatives	1	2	3	4
Config	Vehicle	Wing & Tail	Wing & Canard	Wing, Tail & Canard	Wing
	Fuselage	Cylindrical	Oval	None	
	Pilot Visibility	Synthetic Vision	Conventional		
Mission	Range (nmi)	3000	3500	4000	
	Passengers	100	150	200	
	Mach Number	0.8	0.83	0.85	0.9
Prop	Type	Turbofan	AST Engine	IHPTET	
	Combustor	Conventional	RQL	LPP	
Control	Static Stability	Stable	Unstable	Relaxed	
	Gust control	Conventional	Unloaded		
Aero	Low Speed	Conventional Flaps	Conventional Flaps & Slots	C C	
	High Speed	Conventional	LFC	NLFC	HLFC
Struct	Wing	Aluminum	Titanium	Composite	
	Fuselage	Aluminum	Titanium	Composite	

A morphological matrix can be used to structure candidate technologies

'Most Feasible': fewest identified obstacles to success

TRLs can be used as a proxy for obstacles overcome in development



Research Plan 2:
Decompose existing designs according to functional requirements. Construct morphological matrix from function decomposition, assigning Technology Readiness Level (TRL) values to each option. Use TRL rankings by category as the primary selection criterion to form baseline.

Quantifying Performance

A few metrics for ISRU designs exist in the literature:

- Sizing Totals: Mass (m_{ISRU}) – payload/instrument mass
  - Aggregate mass of all systems directly or indirectly involved in NEO surface operations; excludes return vehicle dry mass
- Mass Payback Ratio (MPR) – reduction in initial mass in LEO
  - $MPR \equiv \frac{\text{mass of resources}}{\text{mass of equipment}} = \frac{m_{fuel} + m_{ox} + m_{samp}}{m_{ISRU}}$
- Power Mass Penalties (PMP) [kg/kW] – habitat power to mass
  - $PMP \equiv \frac{\text{mass of system handling energy}}{\text{demanded energy use capacity}} = \frac{m_{POWER}}{P_{ISRU}}, \frac{m_{HEAT}}{Q_{H,ISRU}}, \frac{m_{COOL}}{Q_{C,ISRU}}$
- Lifetime Embodied Energy – not used in this thesis

Conjecture:
A set of sizing equations with parameters are required to quantify performance

Types of Parameters

Research Question 3:
What parameters are needed to adequately describe a Near Earth Object (NEO) sample return mission involving In-Situ Propellant Production (ISPP)?

Primary
Driving factors

- High variability between subjects makes setting a default value difficult, otherwise inappropriate
- Featured in many and/or highly significant equations
- Need range & nominal value

Secondary
Options & tuning factors

- Needed, but not critical
  - Calibration for model, or overriding defaults
  - Flags for options selected
- Fixed values to reduce confounding, unless input
- Need default value

Preforming Systematic Comparisons

Research Question 1:

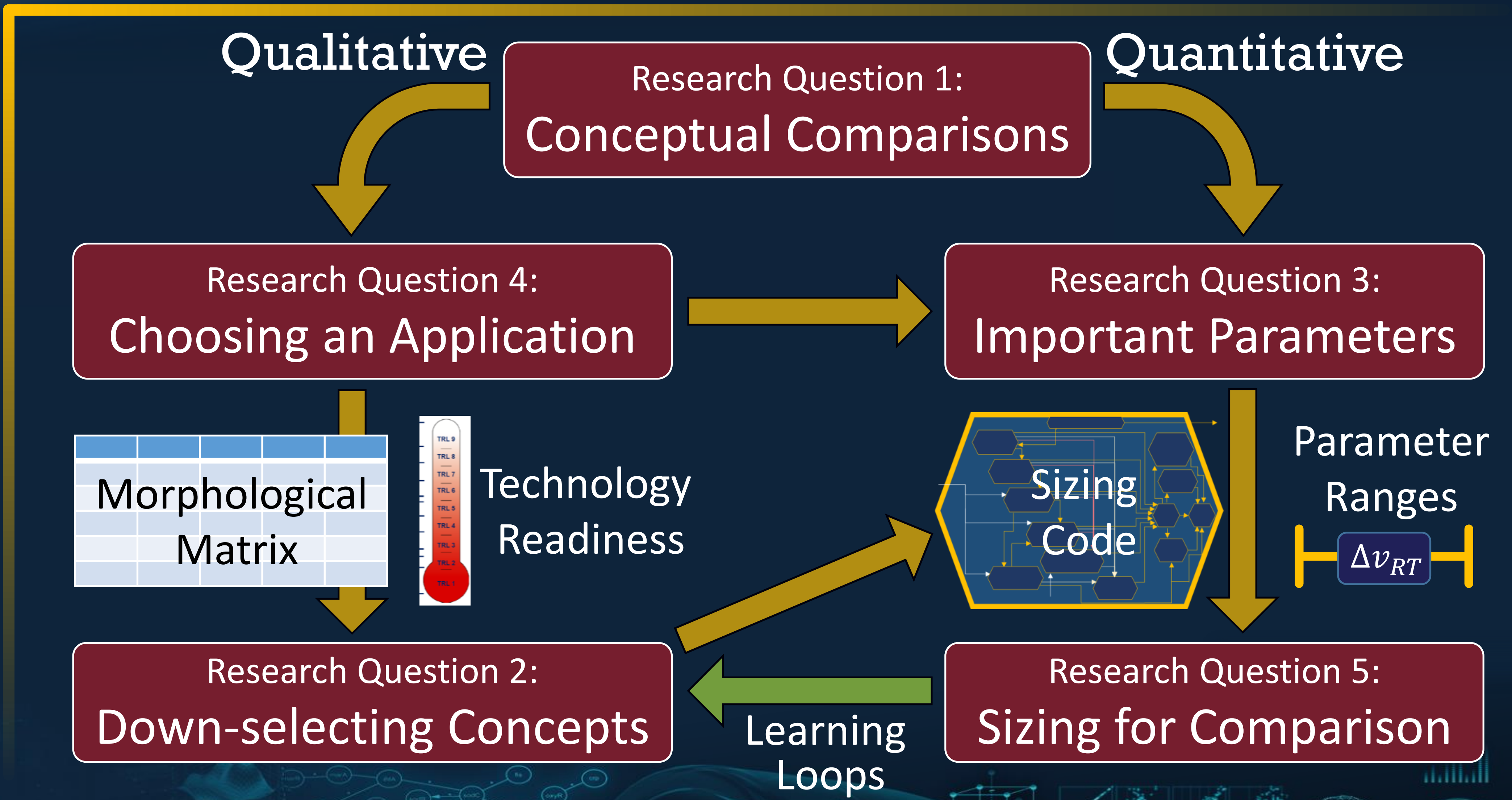
How can comparisons between In-Situ Resource Utilization (ISRU) System of Systems (SoS) be done systematically at the conceptual level?

Qualitative – Morphological Matrix from functional decomposition
Quantitative – Default values and ranges for inputs into sizing code
Application – Provides context for implementation

Conjecture 1:

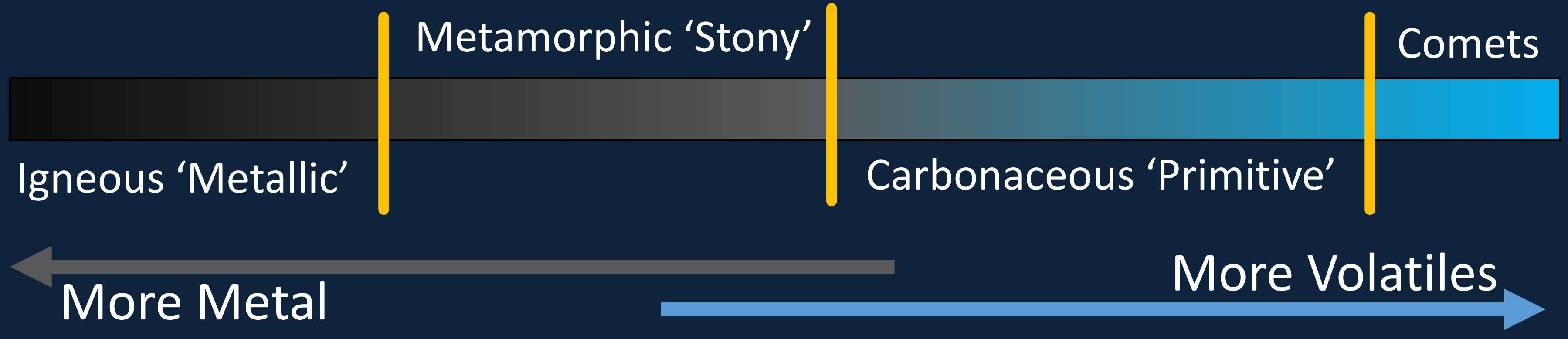
By using qualitative and/or quantitative aspects, design concepts can be compared systematically. Morphological matrices give structure to designs, which can be compared qualitatively with Technology Readiness Levels (TRLs). Sizing codes can be associated with morphology, and used to compare them quantitatively to identify general trends in performance.

A Methodology for Conceptual Comparisons



NEO Space Resources

Research Question 4:
What is the most feasible application for NEO ISRU development presently?



Fabrication | Habitats | Consumables

Space Resource – substances or prevailing conditions with perceived value
Most Feasible – having the fewest identified obstacles to success
NEO Composition – Bell superclasses & comets permit high-level grouping

Policy & Personnel Angles

- Crewed Exploration
  - Greatest demand for ISRU products to offset heavier baseline payloads
  - Unproven ISRU systems on critical path highly risky, but most beneficial
  - Highest consequences of failure, but people are better at fixing things: ISRU maintenance, reliability, & operations is *unsolved problem*
- Policy Angles
  - Outer Space Treaty – limited/no property rights & mining claims
  - Private Investment – very long time horizons, unproven fundamentals
  - Planetary Protection – landers Cat. II, return Cat. V (unrestricted)

Conjecture:
Producing propellant for scientific sample return sidesteps these issues

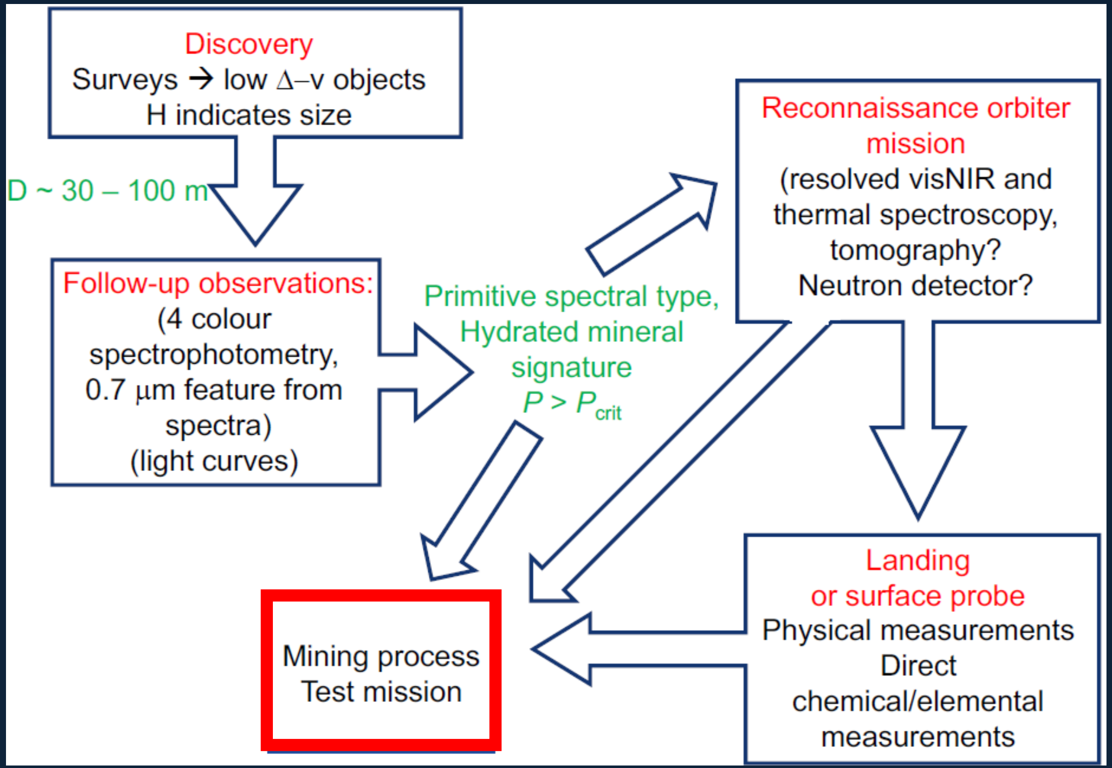
Sample Return Mission

Proposed Name: **SNIPT**

Sample return from
Near earth object with
In-situ
Propellant production
Technology demonstrator

Science objectives could include:

- Study of asteroid regolith, with focus on changes under heating
- Asteroid composition vs. depth
- Test theories on asteroid evolution and formation of early solar system



Conjecture 4:

In-Situ Propellant Production (ISPP) using NEO resources for a sample return mission is the most feasible ISRU SoS application presently.

Green (2018). "Wrap Up: How to Improve Our Knowledge".

ISPP: Propellant Choice Trade Study

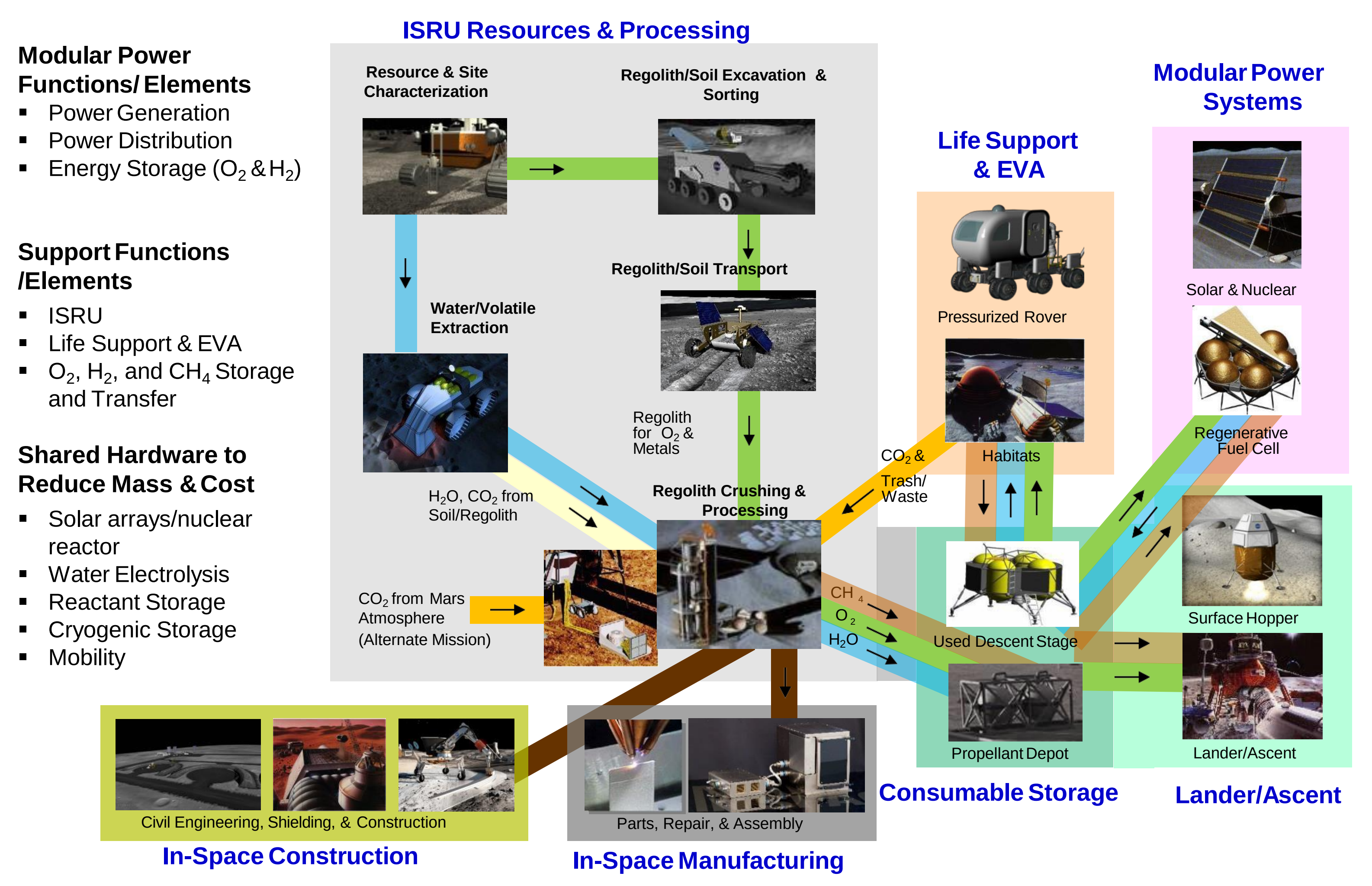
Research Question 5:
How does the selection of the target NEO impact the choice of propellant to be used for the return trip?

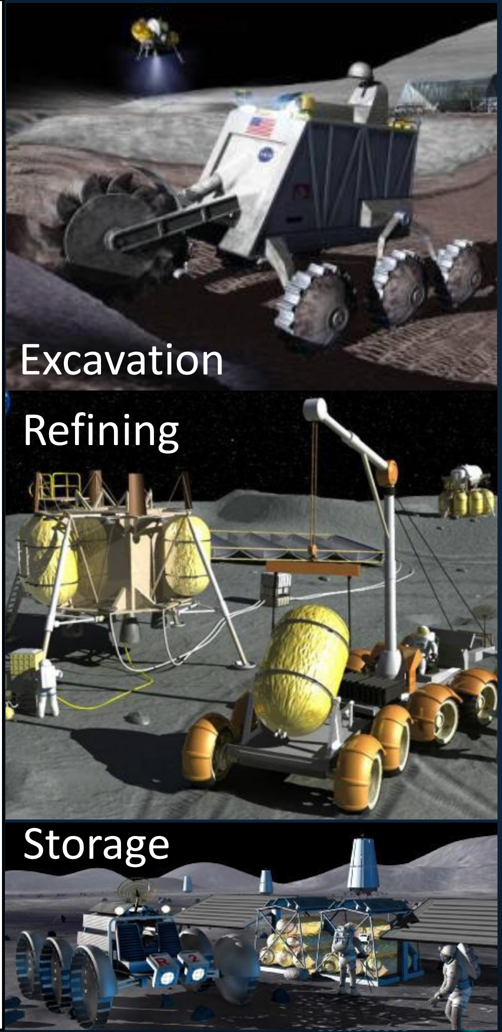
Research Plan 5:
Construct morphological matrix, using functional decomposition. Down-select concepts qualitatively for each propellant considered using TRLs in line with 4Q. Determine input parameters in line with 5Q, then create modules in sizing code to correspond with selected concepts. Verify and validate as appropriate, then screen values using quantitative methods.

Hypothesis 5:
If a less demanding target NEO is selected, then steam ISPP will tend to have the smallest overall plant mass, followed hydrolox, hydrogen, then methalox.
If a more demanding target is selected, this order is reversed.

Hypothesis 5 is subdivided into **Hypotheses 5.1 & 5.2**, to be tested in **Experiments 1 & 2**

NASA Lunar ISRU Concept (2019)

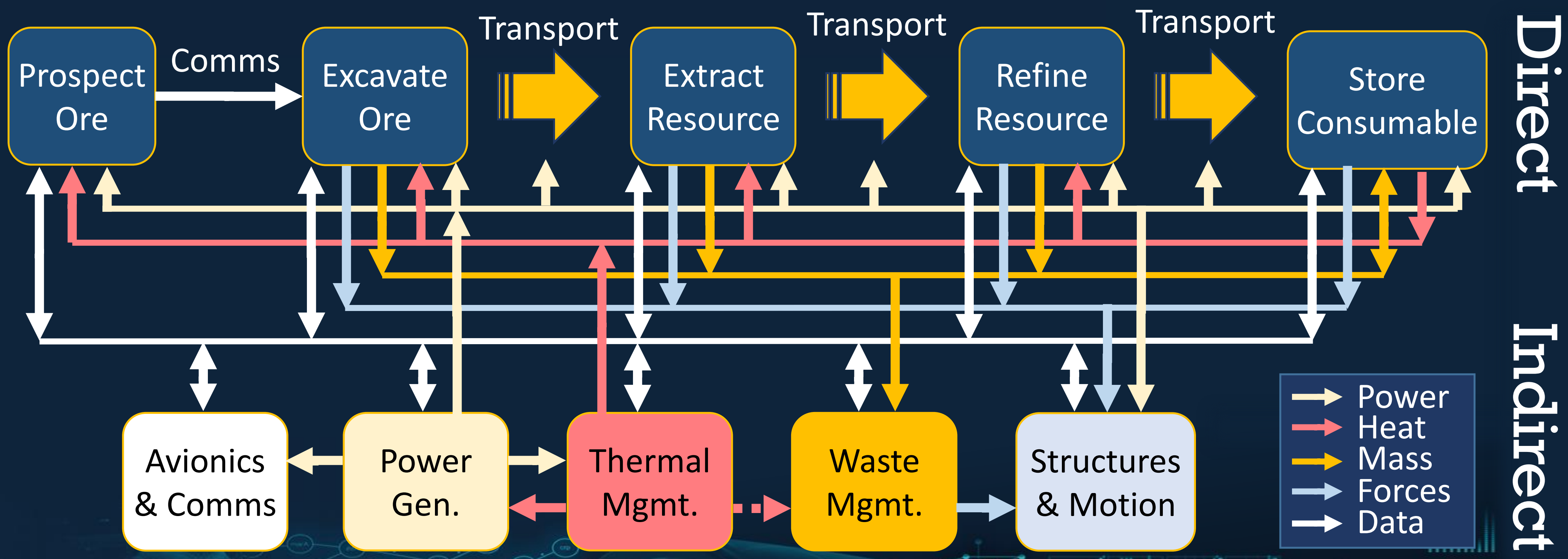




Jakupca, Ian. 2019. "NASA Fuel Cell and Hydrogen Activities". Paper presented at the Annual Merit Review, Department of Energy, April 30.

Functional Decomposition to Systems Level

- Definitions:
  - Resource – substance of value (e.g. water and/or hydrocarbons)
  - Ore – material containing resource in its raw form (e.g. hydrated crystals)
  - Consumable – processed & purified resource ready to be used (e.g. propellants)



Morphology: Existing Concepts

Legend:
- Option for Case Study
- Null Option (not needed)
- Violates Mission Assumpt.
- Unspecified in Literature

$^{8}/_{20}$ shown

Categorization of Existing Concepts Task	Group	Category	Honey Bee APIS (TransAstra Corp.)	Spider (HoneyBee Robotics)	Robotic Asteroid Prospect (Astrotecture / HoneyBee)	Cornucopia (Star Technology & Research)	Hein et al. (Initiative for Interstellar Studies)	RockBreaker (Georgia Tech ASDL)	Konstantin & Mules (Catalyst Corporation)	Surculus Astrum (Univ. of Washington)
Sample Return	Integration	Separation	Single Unit (None)	Single Unit (None)	Single Unit (None)	Detachable Modules	Swarming Craft	Swarming Craft	Swarming Craft	Detachable Modules
		Redunancy	Independent Strings	Independent Strings	Independent Strings	Independent Strings	Multiple Craft	Multiple Craft	Multiple Craft	Multiple Craft
	Return Vehicle	Thrust Class	Solar Thermal	Electrothermal (resistance)	Solar Thermal	Ion Thruster	Solar Sail	Ion Thruster, Solar Sail	Chemical Reaction (liquid)	Electromagnetic (ELF)
		Propellant	Water/Steam	Water/Steam	Water/Steam	Noble Gas - Xenon	N/A	Noble Gas - Argon	Methalox	Water or Noble Gas (Argon
		Chamber Reaction	N/A	N/A	N/A	N/A	N/A	N/A	? (Unspecified)	N/A
		Return Type	Partial / Some Systems	Whole SoS	Whole SoS	Return Vehicles	Return Vehicles	N/A	Return Vehicles	Return Vehicles
Direct ISRU	Prospecting	Local Observations	Precursor, Passive Obs.	Sampling Only	Precursor, Sampling Only	Passive Observation	Active Observation	Active Observation	Active Observation	Active Observation
		Wave Type	Visible Light	N/A	N/A	Visible Light	Visible Light	Radar	Vis. Light, Subatomic Part.	Visible Light, Gamma Rays
		Sampling	N/A	Excavate (automated)	Kinetic Penetrator (smart)	N/A	N/A	? (Unspecified)	N/A	N/A
	Excavation	Containment	Synched Bag	Tube Sleeve	Clamshell Enclosure	Tube Sleeve	Localized Membrane	N/A	Synched Bag	Tube Sleeve
		Cut Rock	Optical Beam (spalling)	Auger Bit	Optical Beam (spalling)	Auger Bit	Optical Beam (spalling)	Beam (laser) & Jet (plasma)	Rotary Cutter	Rotary Cutter
		Powderize	N/A	Cut Debris (Kerf/Spall)	Cut Debris (kerf/spall)	N/A	N/A	Cut Debris (kerf/spall)	Rip/Fracture	Rip/Fracture
		Sorting/Sizing	N/A	N/A	N/A	N/A	N/A	N/A	Centerfugal & Filtration	? (Unspecified)
	Extraction	Heating [Primary]	Focused Sunlight	Resistance (electrical)	Focused Sunlight	N/A	Laser (artificial)	Jet (plasma)	Focused Sunlight	Dielectric (artifcial)
		Beneficiation	N/A	N/A	N/A	N/A	N/A	Fabry-Perot Resonator	Centerfugal & Chemical	Electrostatic Sorting
		Volatile Capture	Cold Trap (condensation)	Cold Trap (condensation)	Cold Trap (condensation)	N/A	Cold Trap (condensation)	N/A	Condenser	? (Unspecified)
	Refining	Make Oxygen	N/A	N/A	N/A	N/A	N/A	N/A	Split Water	? (Unspecified)
		Make Hydrogen	N/A	N/A	N/A	N/A	N/A	N/A	Electrolysis (Unspecified)	? (Unspecified)
		Crack Hydrocarbons	N/A	N/A	N/A	N/A	N/A	N/A	Pyrolysis (Heat)	? (Unspecified)
		Make Methane	N/A	N/A	N/A	N/A	N/A	N/A	? (Unspecified)	N/A
		Quality Control	? (Unspecified)	Process Monitoring	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Storage	Medium	Cryogenic Solid (Ice)	Liquid (Water)	Liquid (Water)	Solid (Regolith)	Cryogenic Solid (Ice)	Solid (Regolith)	Liquid & Granular Soilds	Liquid & Granular Soilds
		Insulation	Sunshield / Shade	Multi-Layer Insulation	? (Unspecified)	? (Unspecified)	Multi-Layer Insulation	? (Unspecified)	Sunshield / Shade	? (Unspecified)
	Material Handling	Granular Solids	N/A	Auger / Screw Feeder	N/A	Auger / Screw Feeder	N/A	Mechanical Pusher	? (Unspecified)	Auger / Screw Feeder
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Pressure Fed (by Heating)	Pressure Fed (by Heating)	N/A	Pressure Fed (by Heating)	Jet (momentum transfer)	? (Unspecified)	? (Unspecified)
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Heating (Volume Increase)	? (Unspecified)	? (Unspecified)	? (Unspecified)
Indirect ISRU	Avionics	Autonomy	? (Unspecified)	? (Unspecified)	Autonomous (if possible)	Autonomous	Autonomous	? (Unspecified)	Automated, Astronauts	Automated
		Computation	Distributed (control boards)	Centralized	Distributed (in ORUs)	Distributed (main & sys.)	Distributed	? (Unspecified)	Centralized (server rack)	? (Unspecified)
		Local Comms	Wired	Wired	Transmitted	Transmitted	Transmitted	Transmitted	Transmitted	Transmitted
		Deep Space Comms	Laser Link	Radio	Radio (steerable antennae)	Radio (Dish)	? (Unspecified)	Radio (Rectenna/Dish)	? (Unspecified)	Laser Link
	Power	Electrical Generation	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Concentrated Solar	Photovoltaic Cells	Fission Reactor
		Energy Storage	Batteries	Batteries	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Beam Transmission	Mirrors	N/A	Mirrors	N/A	? (Unspecified)	Beamed Microwaves	Mirrors	N/A
	Thermal	Heating [Secondary]	? (Unspecified)	Resistance (electrical)	Resistance (electrical)	Resistance (electrical)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Cooling	Radiators	? (Unspecified)	Radiators	? (Unspecified)	? (Unspecified)	Passive	? (Unspecified)	? (Unspecified)
		Heat Exchangers	Cold Plate	Finned	? (Unspecified)	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Distribution	Water Loop	Peltier Effect (electrical)	Loop - (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Wastes	Tailings & Overburden	Secure in Place	Eject into Space	? (Unspecified)	N/A	? (Unspecified)	Storage/Reuse	? (Unspecified)	Storage/Reuse
		Byproducts & Excess	? (Unspecified)	? (Unspecified)	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	Storage/Reuse	? (Unspecified)
	Structures	Support Structure	Inflatable	Truss & Recessed Lattice	Space Frame	Central Bus / Cylindrical	? (Unspecified)	? (Unspecified)	Truss, collapsible	? (Unspecified)
		Positioning	Anchor / Harpoon	Friction with Excavator	Inflatable Airbags	Anchor / Harpoon	RCS Thrusters	RCS Thrusters	RCS Thrusters	Anchor / Harpoon
		Relative Motion	Robotic Joints	Robotic Joints	RCS Thrusters	Robotic Joints	RCS Thrusters	RCS Thrusters	RCS Thrusters	RCS Thrusters
		Rotation Control	Friction with Containment	? (Unspecified)	N/A	? (Unspecified)	Selective Ablation	Selective Ablation	N/A	? (Unspecified)
		Main Source:	Sercel, 2016	Zacny et al., 2016	Cohen et al., 2013	Buet et al., 2013	Hein et al., 2019	Vanmali et al., 2005	Daniel Suarez, 2019	Andrews et al., 2015

Morphology: Existing Concepts

Legend:
- Option for Case Study
- Null Option (not needed)
- Violates Mission Assumpt.
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$^{8}/_{20}$ shown

Task	Group	Category	Honey Bee APIS (TransAstra Corp.)	Spider (HoneyBee Robotics)	Robotic Asteroid Prospect (Astrotecture / HoneyBee)	Cornucopia (Star Technology & Research)	Hein et al. (Initiative for Interstellar Studies)	RockBreaker (Georgia Tech ASDL)	Konstantin & Mules (Catalyst Corporation)	Surculus Astrum (Univ. of Washington)
Sample Return	Integration	Separation	Single Unit (None)	Single Unit (None)	Single Unit (None)	Detachable Modules	Swarming Craft	Swarming Craft	Swarming Craft	Detachable Modules
		Redunancy	Independent Strings	Independent Strings	Independent Strings	Independent Strings	Multiple Craft	Multiple Craft	Multiple Craft	Multiple Craft
	Return Vehicle	Thrust Class	Solar Thermal	Electrothermal (resistance)	Solar Thermal	Ion Thruster	Solar Sail	Ion Thruster, Solar Sail	Chemical Reaction (liquid)	Electromagnetic (ELF)
		Propellant	Water/Steam	Water/Steam	Water/Steam	Noble Gas - Xenon	N/A	Noble Gas - Argon	Methalox	Water or Noble Gas (Argon
		Chamber Reaction	N/A	N/A	N/A	N/A	N/A	N/A	? (Unspecified)	N/A
		Return Type	Partial / Some Systems	Whole SoS	Whole SoS	Return Vehicles	Return Vehicles	N/A	Return Vehicles	Return Vehicles
Direct ISRU	Prospecting									a Rays
	Excavation									
	Extraction									
	Refining									
		Make Hydrogen	N/A	N/A	N/A	N/A	N/A	N/A	Electrolysis (Unspecified)	? (Unspecified)
		Crack Hydrocarbons	N/A	N/A	N/A	N/A	N/A	N/A	Pyrolysis (Heat)	? (Unspecified)
		Make Methane	N/A	N/A	N/A	N/A	N/A	N/A	? (Unspecified)	N/A
		Quality Control	? (Unspecified)	Process Monitoring	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Storage	Medium	Cryogenic Solid (Ice)	Liquid (Water)	Liquid (Water)	Solid (Regolith)	Cryogenic Solid (Ice)	Solid (Regolith)	Liquid & Granular Soilds	Liquid & Granular Soilds
		Insulation	Sunshield / Shade	Multi-Layer Insulation	? (Unspecified)	? (Unspecified)	Multi-Layer Insulation	? (Unspecified)	Sunshield / Shade	? (Unspecified)
	Material Handling	Granular Solids	N/A	Auger / Screw Feeder	N/A	Auger / Screw Feeder	N/A	Mechanical Pusher	? (Unspecified)	Auger / Screw Feeder
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Pressure Fed (by Heating)	Pressure Fed (by Heating)	N/A	Pressure Fed (by Heating)	Jet (momentum transfer)	? (Unspecified)	? (Unspecified)
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Heating (Volume Increase)	? (Unspecified)	? (Unspecified)	? (Unspecified)
Indirect ISRU	Avionics									
	Power									
	Thermal									
	Wastes	Tailings & Overburden	Secure in Place	Eject into Space	? (Unspecified)	N/A	? (Unspecified)	Storage/Reuse	? (Unspecified)	Storage/Reuse
		Byproducts & Excess	? (Unspecified)	? (Unspecified)	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	Storage/Reuse	? (Unspecified)
	Structures	Support Structure	Inflatable	Truss & Recessed Lattice	Space Frame	Central Bus / Cylindrical	? (Unspecified)	? (Unspecified)	Truss, collapsible	? (Unspecified)
		Positioning	Anchor / Harpoon	Friction with Excavator	Inflatable Airbags	Anchor / Harpoon	RCS Thrusters	RCS Thrusters	RCS Thrusters	Anchor / Harpoon
		Relative Motion	Robotic Joints	Robotic Joints	RCS Thrusters	Robotic Joints	RCS Thrusters	RCS Thrusters	RCS Thrusters	RCS Thrusters
		Rotation Control	Friction with Containment	? (Unspecified)	N/A	? (Unspecified)	Selective Ablation	Selective Ablation	N/A	? (Unspecified)
		Main Source:	Sercel, 2016	Zacny et al., 2016	Cohen et al., 2013	Buet et al., 2013	Hein et al., 2019	Vanmali et al., 2005	Daniel Suarez, 2019	Andrews et al., 2015

Research Question 2:
What is the most feasible set of morphological options for an In-Situ Propellant Production (ISPP) System of Systems (SoS) using Near Earth Object (NEO) resources based upon technological readiness alone?

Hypothesis 2:
If Technology Readiness Levels (TRLs) are used to rank morphological options, then the most feasible concept will use concentrated sunlight to sublimate gasses in a sealed chamber, with a capsule returning samples.

Morphological Matrix: Option Sources

Introduction
Motivation
Methodology
Implementation
Qualitative
Quantitative
Experiment 1
Experiment 2
Conclusions

Shaded by Source of Option

Task	Group	Category	Morphological Options						Null?
Sample Return	Integration	Separation	Single Unit (None)	Detachable Modules	Subsequent Missions	Swarming Craft			
		Redundancy	Single String (None)	Independent Strings	Cross-Strapped Strings	Multiple Craft			
	Return Vehicle	Propulsion	Chemical Reaction (liquid)	Solar Thermal	Nuclear Thermal	Electrothermal	Electromagnetic	Ion Thruster	
		Propellant	Water/Steam	Hydrogen	Hydrolox	Methalox			
		Chamber Reaction	Fuel Rich	Stoichiometric	Oxidizer Rich				N/A
		Return Type	Partial / Some Systems	Whole SoS	Return Vehicles				
Direct ISRU	Prospecting	Local Observations	Passive Observation	Active Observation	Seismic Survey	Orbit Gravimetry			
		Wave Type	Far Infrared / Thermal	Near Infrared	Visible Light	Radar	Sound / Mechanical	Subatomic Particles	N/A
		Sampling	Kinetic Penetrator (smart)	Impactor (dumb)	Excavate (automated)	Touch & Go (TAGSAM)	Skyhook / Harpoon		N/A
	Excavation	Containment	Clamshell Enclosure	Synched Bag	Tube Sleeve	Localized Membrane			
		Cut Rock	Auger Bit	Corer	Percussive Drill	Optical Beam (Spalling)	Jet (plasma)	Rotary Cutter	
		Powderize	Pneumatic Probes	Borehole Heating	Rip/Fracture	Cut Debris (kerf/spall)	Crush		N/A
		Sorting/Sizing	Filtration	Centrifugal (density)	Sieves				N/A
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Resistance (electrical)	Dielectric (microwave)	Jet (Heated)	Induction	
		Beneficiation	Centrifugal (density)	Magnetic Separation	Electrostatic Separation	Molten Powderization	Reformer	Leachate (chemical)	N/A
		Volatile Capture	Cold Trap (Deposition)	Condenser	Sorbents	Vacuum Distillation			
	Refining	Make Oxygen	Carbothermal Reduction	Split Water	Metal Electrolysis	Ionic Liquid Reduction			N/A
		Make Hydrogen	Acidic Electrolysis (Voltage)	Alkaline Electrolysis	Solid Oxide Electrolysis	Thermolysis (Heat)	Photocatalytic (Light)		N/A
		Crack Hydrocarbons	Reverse Water Gas Shift	Steam Reforming	Pyrolysis (Heat)	Thermal Oxidation (Burn)	Fluid Catalytic		N/A
		Make Methane	Fischer-Tropsch Process	Sabatier Process	Photocatalytic				N/A
		Quality Control	Process Monitoring	Output Check	Batch Quarantine				
	Storage	Medium	Cryogenic Liquid	Cryogenic Solid	Pressurized Gas	Granular Solids	Chemical	Gel	
		Insulation	Multi-Layer Insulation	Coatings (External)	Sun Shade / Sunshield	Dewar / Vacuum Shell	Body Lining (Internal)		
	Material Handling	Granular Solids	Mechanical Pusher	Auger / Screw Feeder	Pneumatics	Rotating Feeder ('Airlock')	Electrostatic		N/A
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Pressure Differential	Flow Ionization	Jet (momentum transfer)			
		Work Input	Heating (Volume Increase)	Shaft Work	Linear Actuator	Compressor (Pressure)	Ref. Frame (Spin)		
Indirect ISRU	Avionics	Autonomy	Autonomous	Automated	Remote				
		Computation	Centralized	Distributed	String Isolated				
		Local Comms	Transmitted	Wired					
		Deep Space Comms	Powerful Radio (DSN)	Laser Link	Repeaters				
	Power	Electrical Generation	Concentrated Solar	Photovoltaic Cells	Thermal Gradient	Radioactive Decay (RTG)	Fission Reactor		
		Energy Storage	Batteries	Capacitors	Chemical / Fuel Cell	Thermal Mass			N/A
		Beam Transmission	Fiber Optics	Mirrors	Beamed Microwaves				N/A
	Thermal	Heating [Secondary]	Focused Sunlight	Light (lamp/laser)	Resistance (electrical)	Chemical Reaction			
		Cooling	Passive	Radiators	Barbecue Roll	Heat Storage	Sublimation		
		Heat Exchangers	Cold Plate	Finned	Tubular	Phase Change / Cycle			N/A
		Distribution	Water Loop	Refrigerant Loop	Heat Pipes	Peltier Effect (Electrical)	Thermoacoustics		
	Wastes	Tailings & Overburden	Eject into Space	Storage/Reuse	Deposit into Source	Secure in Place			
		Byproducts & Excess	Vent into Space	Storage/Reuse	Inject into Source				
	Structures	Support Structure	Central Bus / Cylindrical	Truss / Space Frame	Panel / Stressed Skin	Floors / Support Decks	Inflatable		
		Positioning	RCS Thrusters	Inflatable Airbags	Anchor / Harpoon	Guy Wires / Tensegrity	Friction with Excavator	Microspines / Claw	
		Relative Motion	RCS Thrusters	Main Thrusters	Robotic Joints	Cable Tension	Internal Gas Jets	Reaction Wheels	
		Rotation Control	Selective Ablation	Thruster Pods	Orbital Nudging	Friction with Containment	Impactor		N/A

Shading:
Source
Microgravity TRL
Implementation

43 Categories
205 Options
$2.7*10^{28}$ Combos
(27 Octillion, short scale)

	Source
61%	Existing Concepts
25%	Space & ISRU Field
13%	Other Fields

Morphological Matrix: Microgravity TRLs

Shaded Options: Microgravity TRLs

Task	Group	Category	Morphological Options						Null?
Sample Return	Integration	Separation	Single Unit (None)	Detachable Modules	Subsequent Missions	Swarming Craft			
		Redundancy	Single String (None)	Independent Strings	Cross-Strapped Strings	Multiple Craft			
	Return Vehicle	Propulsion	Chemical Reaction (liquid)	Solar Thermal	Nuclear Thermal	Electrothermal	Electromagnetic	Ion Thruster	
		Propellant	Water/Steam	Hydrogen	Hydrolox	Methalox			
		Chamber Reaction	Fuel Rich	Stoichiometric	Oxidizer Rich				N/A
		Return Type	Whole SoS	Partial / Some Systems	Return Vehicles				
Direct ISRU	Prospecting	Local Observations	Passive Observation	Active Observation	Seismic Survey	Orbit Gravimetry			
		Wave Type	Far Infrared / Thermal	Near Infrared	Visible Light	Radar	Sound / Mechanical	Subatomic Particles	N/A
		Sampling	Kinetic Penetrator (smart)	Impactor (dumb)	Excavate (automated)	Touch & Go (TAGSAM)	Skyhook / Harpoon		N/A
	Excavation	Containment	Clamshell Enclosure	Synched Bag	Tube Sleeve	Localized Membrane			
		Cut Rock	Auger Bit	Corer	Percussive Drill	Optical Beam (spalling)	Jet (plasma)	Rotary Cutter	
		Powderize	Pneumatic Probes	Borehole Heating	Rip/Fracture	Cut Debris (kerf/spall)	Crush		N/A
		Sorting/Sizing	Filtration	Centrifugal (density)	Sieves				N/A
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Resistance (electrical)	Dielectric (microwave)	Jet (Heated)	Induction	
		Beneficiation	Centrifugal (Density)	Magnetic Separation	Electrostatic Separation	Molten Powderization	Reformer	Leachate (Chemical)	N/A
		Volatile Capture	Cold Trap (Deposition)	Condenser	Sorbents	Vacuum Distillation			
	Refining	Make Oxygen	Carbothermal Reduction	Split Water	Metal Electrolysis	Ionic Liquid Reduction			N/A
		Make Hydrogen	Acidic Electrolysis	Alkaline Electrolysis	Solid Oxide Electrolysis	Thermolysis (Heat)	Photocatalytic (Light)		N/A
		Crack Hydrocarbons	Reverse Water Gas Shift	Steam Reforming	Pyrolysis (Heat)	Thermal Oxidation (Burn)	Fluid Catalytic		N/A
		Make Methane	Fischer-Tropsch Process	Sabatier Process	Photocatalytic				N/A
		Quality Control	Process Monitoring	Output Check	Batch Quarantine				
	Storage	Medium	Cryogenic Liquid	Cryogenic Solid	Pressurized Gas	Granular Solid	Chemical	Gel	
		Insulation	Multi-Layer Insulation	Coatings (External)	Sun Shade / Sunshield	Body Lining (Internal)	Dewar / Vacuum Shell		
	Material Handling	Granular Solids	Mechanical Pusher	Auger / Screw Feeder	Pneumatics	Rotating Feeder ('Airlock')	Electrostatic		N/A
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Jet (momentum transfer)	Pressure Differential	Flow Ionization			
		Work Input	Heating (Volume Increase)	Shaft Work (Pump)	Linear Actuator	Compressor (Pressure)	Reference Frame (Spin)		
Indirect ISRU	Avionics	Autonomy	Autonomous	Automated	Remote				
		Computation	Centralized	Distributed	String Isolated				
		Local Comms	Transmitted	Wired					
		Deep Space Comms	Powerful Radio (DSN)	Laser Link	Repeaters				
	Power	Electrical Generation	Concentrated Solar Power	Photovoltaic Cells	Thermal Gradient	Radioactive Decay (RTG)	Fission Reactor		
		Energy Storage	Batteries	Capacitors	Chemical / Fuel Cell	Thermal Mass			N/A
		Beam Transmission	Fiber Optics	Mirrors	Beamed Microwaves				N/A
	Thermal	Heating [Secondary]	Focused Sunlight	Light (lamp/laser)	Resistance (electrical)	Chemical Reaction			
		Cooling	Passive	Radiators	Barbecue Roll	Heat Storage	Sublimation		
		Heat Exchanger	Cold Plate	Finned	Tubular	Phase Change / Cycle			N/A
		Distribution	Water Loop	Refrigerant Loop	Heat Pipes	Peltier Effect (electrical)	Thermoacoustics		
	Wastes	Tailings & Overburden	Eject into Space	Storage/Reuse	Deposit in Source	Secure in Place			
		Byproducts & Excess	Vent into Space	Storage/Reuse	Inject into Source				
	Structures	Support Structure	Central Bus / Cylindrical	Truss / Space Frame	Panel / Stressed Skin	Floors / Support Decks	Inflatable		
		Positioning	RCS Thrusters	Inflatable Airbags	Harpoon / Anchor	Guy Wires / Tensegrity	Microspines / Claw	Friction with Excavator	
		Relative Motion	RCS Thrusters	Main Thrusters	Robotic Joints	Cable Tension	Internal Gas Jets	Reaction Wheels	
		Rotation Control	Selective Ablation	Thruster Pods	Orbital Nudging	Friction with Containment	Impactor		N/A

Shading:
Source
Microgravity TRL
Implementation

128 µ-g TRLs documented, more in work

TRLs (TBD)
1
2
3
4
5
6
7
8
9
N/A

Morphological Matrix: Selections

Task	Group	Category	HoneyBee {tweaked} Steam - Optical	Concept 'S' Steam - Electric	Concept 'H' Hydrogen	Concept 'HO' Hydrolox	Concept 'MO' Methalox
Sample Return	Integration	Separation	Single Unit (None)	Single Unit (None)	Single Unit (None)	Single Unit (None)	Single Unit (None)
		Redunancy	Independent Strings	Cross-Strapped Strings	Cross-Strapped Strings	Cross-Strapped Strings	Cross-Strapped Strings
	Return Vehicle	Propulsion	Solar Thermal	Solar Thermal	Electromagnetic (VASMIR)	Chemical Reaction (liquid)	Chemical Reaction (liquid)
		Propellant	Water/Steam	Water/Steam	Hydrogen	Hydrolox	Methalox
		Chamber Reaction	N/A	N/A	N/A	Fuel Rich	Fuel Rich
		Return Type	Some Systems Left Behind	Return Vehicles	Return Vehicles	Return Vehicles	Return Vehicles
Direct ISRU	Prospecting	Local Observations	*Active Observation*	Active Observation	Active Observation	Active Observation	Active Observation
		Wave Type	*Radar*	Radar	Radar	Radar	Radar
		Sampling	N/A	N/A	N/A	N/A	N/A
	Excavation	Containment	Synched Bag	Tube Sleeve	Tube Sleeve	Tube Sleeve	Tube Sleeve
		Cut Rock	Optical Beam (spalling)	Corer	Corer	Corer	Corer
		Powderize	N/A	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)
		Sorting/Sizing	N/A	N/A	N/A	N/A	N/A
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)
		Beneficiation	N/A	Filtration	Filtration	Filtration	Filtration
		Volatile Capture	Cold Trap (Condensation)	Sorbents	Sorbents	Sorbents	Sorbents
	Refining	Make Oxygen	N/A	N/A	N/A	Split Water	Split Water
		Make Hydrogen	N/A	N/A	Acidic Electrolysis (Voltage)	Acidic Electrolysis (Voltage)	Acidic Electrolysis (Voltage)
		Crack Hydrocarbons	N/A	N/A	N/A	N/A	Pyrolysis (Heat)
		Make Methane	N/A	N/A	N/A	N/A	Sabatier Process
		Quality Control	*Process Monitoring*	Process Monitoring	Process Monitoring	Process Monitoring	Process Monitoring
	Storage	Medium	Cryogenic Solid	Cryogenic Solid	Cryogenic Liquid	Cryogenic Liquid	Cryogenic Liquid
		Insulation	Sunshield / Shade	Multi-Layer Insulation	Multi-Layer Insulation	Multi-Layer Insulation	Multi-Layer Insulation
	Material Handling	Granular Solids	N/A	Auger / Screw Feeder	Auger / Screw Feeder	Auger / Screw Feeder	Auger / Screw Feeder
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Pressure Differential	Pressure Differential	Pressure Differential	Pressure Differential
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)
Indirect ISRU	Avionics	Autonomy	*Automated*	Automated	Automated	Automated	Automated
		Computation	Distributed	Distributed	Distributed	Distributed	Distributed
		Local Comms	Wired	Wired	Wired	Wired	Wired
		Deep Space Comms	Laser Link	Powerful Radio (DSN)	Powerful Radio (DSN)	Powerful Radio (DSN)	Powerful Radio (DSN)
	Power	Electrical Generation	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells
		Energy Storage	Batteries	Batteries	Batteries	Batteries	Batteries
		Beam Transmission	Mirrors	N/A	N/A	N/A	N/A
	Thermal	Heating [Secondary]	*Resistance (electrical)*	Resistance (electrical)	Resistance (electrical)	Resistance (electrical)	Resistance (electrical)
		Cooling	Radiators	Radiators	Radiators	Radiators	Radiators
		Heat Exchanger	Cold Plate	Finned	Finned	Finned	Finned
		Distribution	Water Loop	Refrigerant Loop	Refrigerant Loop	Refrigerant Loop	Refrigerant Loop
	Wastes	Tailings & Overburden	Secure in Place	Storage/Reuse	Storage/Reuse	Storage/Reuse	Storage/Reuse
		Byproducts & Excess	*Vent into Space*	Storage/Reuse	Storage/Reuse	Storage/Reuse	Storage/Reuse
	Structures	Support Structure	Inflatable	Panel / Stressed Skin	Panel / Stressed Skin	Panel / Stressed Skin	Panel / Stressed Skin
		Positioning	Anchor / Harpoon	Microspines / Claw	Microspines / Claw	Microspines / Claw	Microspines / Claw
		Relative Motion	Robotic Joints	Robotic Joints	Robotic Joints	Robotic Joints	Robotic Joints
		Rotation Control	Friction with Containment	Selective Ablation	Selective Ablation	Selective Ablation	Selective Ablation

Shading:
Source
Microgravity TRL
Implementation

Hydrolox concept has fewest low μ-g TRL options

Concept	TRLs < 6
HoneyBee	10
Water	6
Hydrogen	5
Hydrolox	**4**
Methalox	6

TRLs (TBD)
1
2
3
4
5
6
7
8
9
N/A

Morphological Matrix: Selections

Task	Group	Category (Selected Options for Concepts)	HoneyBee {tweaked} Steam - Optical	Concept 'S' Steam - Electric	Concept 'H' Hydrogen	Concept 'HO' Hydrolox	Concept 'MO' Methalox
Sample Return	Integration	Separation	Single Unit (None)	Single Unit (None)	Single Unit (None)	Single Unit (None)	Single Unit (None)
		Redunancy	Independent Strings	Cross-Strapped Strings	Cross-Strapped Strings	Cross-Strapped Strings	Cross-Strapped Strings
	Return Vehicle	Propulsion	Solar Thermal	Solar Thermal	Electromagnetic (VASMIR)	Chemical Reaction (liquid)	Chemical Reaction (liquid)
		Propellant	Water/Steam	Water/Steam	Hydrogen	Hydrolox	Methalox
		Chamber Reaction	N/A	N/A	N/A	Fuel Rich	Fuel Rich
		Return Type	Some Systems Left Behind	Return Vehicles	Return Vehicles	Return Vehicles	Return Vehicles
Direct ISRU	Prospecting	Local Observations	*Active Observation*	Active Observation	Active Observation	Active Observation	Active Observation
		Wave Type	*Radar*	Radar	Radar	Radar	Radar
		Sampling	N/A	N/A	N/A	N/A	N/A
	Excavation	Containment	Synched Bag	Tube Sleeve	Tube Sleeve	Tube Sleeve	Tube Sleeve
		Cut Rock	Optical Beam (spalling)	Corer	Corer	Corer	Corer
		Powderize	N/A	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)
		Sorting/Sizing	N/A	N/A	N/A	N/A	N/A
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)
		Beneficiation	N/A	Filtration	Filtration	Filtration	Filtration
		Volatile Capture	Cold Trap (Condensation)	Sorbents	Sorbents	Sorbents	Sorbents
	Refining	Make Oxygen	N/A	N/A	N/A	Split Water	Split Water
		Make Hydrogen	N/A	N/A	Acidic Electrolysis (Voltage)	Acidic Electrolysis (Voltage)	Acidic Electrolysis (Voltage)
		Crack Hydrocarbons	N/A	N/A	N/A	N/A	Pyrolysis (Heat)
		Make Methane	N/A	N/A	N/A	N/A	Sabatier Process
		Quality Control	*Process Monitoring*	Process Monitoring	Process Monitoring	Process Monitoring	Process Monitoring
	Storage	Medium	Cryogenic Solid	Cryogenic Solid	Cryogenic Liquid	Cryogenic Liquid	Cryogenic Liquid
		Insulation	Sunshield / Shade	Multi-Layer Insulation	Multi-Layer Insulation	Multi-Layer Insulation	Multi-Layer Insulation
	Material Handling	Granular Solids	N/A	Auger / Screw Feeder	Auger / Screw Feeder	Auger / Screw Feeder	Auger / Screw Feeder
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Pressure Differential	Pressure Differential	Pressure Differential	Pressure Differential
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)
Indirect ISRU	Avionics	Autonomy	*Automated*	Automated	Automated	Automated	Automated
		Computation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Local Comms	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Deep Space Comms	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Power	Electrical Generation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Energy Storage	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Beam Transmission	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Thermal	Heating [Secondary]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Cooling	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Heat Exchanger	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Distribution	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Wastes	Tailings & Overburden	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Byproducts & Excess	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Structures	Support Structure	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Positioning	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Relative Motion	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Rotation Control	Friction with Containment	Selective Ablation	Selective Ablation	Selective Ablation	Selective Ablation

Result 2:
The hydrogen-oxygen (hydrolox) propellant design selected through narrowing down options using TRLs should act as a better baseline for comparison than the Honey Bee.

Shading:
Source
Microgravity TRL
Implementation

Hydrolox concept has fewest low μ-g TRL options

Concept	TRLs < 6
HoneyBee	10
Water	6
Hydrogen	5
Hydrolox	**4**
Methalox	6

TRLs (TBD)
1
2
3
4
5
6
7
8
9
N/A

Morphological Matrix: Implementation

Task	Group	Category	HoneyBee {tweaked} Steam - Optical	Concept 'S' Steam - Electric	Concept 'H' Hydrogen	Concept 'HO' Hydrolox	Concept 'MO' Methalox
Sample Return	Integration	Separation	Single Unit (None)	Single Unit (None)	Single Unit (None)	Single Unit (None)	Single Unit (None)
		Redunancy	Independent Strings	Cross-Strapped Strings	Cross-Strapped Strings	Cross-Strapped Strings	Cross-Strapped Strings
	Return Vehicle	Propulsion	Solar Thermal	Solar Thermal	Electromagnetic (VASMIR)	Chemical Reaction (liquid)	Chemical Reaction (liquid)
		Propellant	Water/Steam	Water/Steam	Hydrogen	Hydrolox	Methalox
		Chamber Reaction	N/A	N/A	N/A	Fuel Rich	Fuel Rich
		Return Type	Some Systems Left Behind	Return Vehicles	Return Vehicles	Return Vehicles	Return Vehicles
Direct ISRU	Prospecting	Local Observations	*Active Observation*	Active Observation	Active Observation	Active Observation	Active Observation
		Wave Type	*Radar*	Radar	Radar	Radar	Radar
		Sampling	N/A	N/A	N/A	N/A	N/A
	Excavation	Containment	Synched Bag	Tube Sleeve	Tube Sleeve	Tube Sleeve	Tube Sleeve
		Cut Rock	Optical Beam (spalling)	Corer	Corer	Corer	Corer
		Powderize	N/A	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)	Cut Debris (Kerf/Spall)
		Sorting/Sizing	N/A	N/A	N/A	N/A	N/A
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)
		Beneficiation	N/A	Filtration	Filtration	Filtration	Filtration
		Volatile Capture	Cold Trap (Condensation)	Sorbents	Sorbents	Sorbents	Sorbents
	Refining	Make Oxygen	N/A	N/A	N/A	Split Water	Split Water
		Make Hydrogen	N/A	N/A	Acidic Electrolysis (Voltage)	Acidic Electrolysis (Voltage)	Acidic Electrolysis (Voltage)
		Crack Hydrocarbons	N/A	N/A	N/A	N/A	Pyrolysis (Heat)
		Make Methane	N/A	N/A	N/A	N/A	Sabatier Process
		Quality Control	*Process Monitoring*	Process Monitoring	Process Monitoring	Process Monitoring	Process Monitoring
	Storage	Medium	Cryogenic Solid	Cryogenic Solid	Cryogenic Liquid	Cryogenic Liquid	Cryogenic Liquid
		Insulation	Sunshield / Shade	Multi-Layer Insulation	Multi-Layer Insulation	Multi-Layer Insulation	Multi-Layer Insulation
	Material Handling	Granular Solids	N/A	Auger / Screw Feeder	Auger / Screw Feeder	Auger / Screw Feeder	Auger / Screw Feeder
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Pressure Differential	Pressure Differential	Pressure Differential	Pressure Differential
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)	Shaft Work (Pump, Auger)
Indirect ISRU	Avionics	Autonomy	*Automated*	Automated	Automated	Automated	Automated
		Computation	Distributed	Distributed	Distributed	Distributed	Distributed
		Local Comms	Wired	Wired	Wired	Wired	Wired
		Deep Space Comms	Laser Link	Powerful Radio (DSN)	Powerful Radio (DSN)	Powerful Radio (DSN)	Powerful Radio (DSN)
	Power	Electrical Generation	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells
		Energy Storage	Batteries	Batteries	Batteries	Batteries	Batteries
		Beam Transmission	Mirrors	N/A	N/A	N/A	N/A
	Thermal	Heating [Secondary]	*Resistance (electrical)*	Resistance (electrical)	Resistance (electrical)	Resistance (electrical)	Resistance (electrical)
		Cooling	Radiators	Radiators	Radiators	Radiators	Radiators
		Heat Exchanger	Cold Plate	Finned	Finned	Finned	Finned
		Distribution	Water Loop	Refrigerant Loop	Refrigerant Loop	Refrigerant Loop	Refrigerant Loop
	Wastes	Tailings & Overburden	Secure in Place	Storage/Reuse	Storage/Reuse	Storage/Reuse	Storage/Reuse
		Byproducts & Excess	*Vent into Space*	Storage/Reuse	Storage/Reuse	Storage/Reuse	Storage/Reuse
	Structures	Support Structure	Inflatable	Panel / Stressed Skin	Panel / Stressed Skin	Panel / Stressed Skin	Panel / Stressed Skin
		Positioning	Anchor / Harpoon	Micropines / Claw	Microspines / Claw	Microspines / Claw	Microspines / Claw
		Relative Motion	Robotic Joints	Robotic Joints	Robotic Joints	Robotic Joints	Robotic Joints
		Rotation Control	Friction with Containment	Selective Ablation	Selective Ablation	Selective Ablation	Selective Ablation

Shading:
Source
Microgravity TRL
Implementation

Partial sizing done, on par with avg. existing sections

Concept	Some Sizing
HoneyBee	44%
Water	58%
Hydrogen	61%
Hydrolox	62%
Methalox	63%
Average	**58%**

	Implementation
40%	Reasonable
18%	Limited
42%	Not Sized

Key Parameters of Interest

Research Question 3:

What parameters are needed to adequately describe a Near Earth Object (NEO) sample return mission involving In-Situ Propellant Production (ISPP)?

$PROP\_TYPE$
Chemical species to be produced by SoS

Δv_{RT} [km/s]
change in velocity from NEO to LEO

t_{STAY} [days]
Time between NEO arrival and departure

m_{PAY} [kg]
Mass of payload to be returned to LEO

Mission Characteristics

t_{PERIOD} [hr]
Period of NEO rotation about its axis

D_{min} [AU]
Min. distance from sun during mission

D_{max} [AU]
Max. distance from sun during mission

Solar Radiation Effects

C_H [%wt]
Concentration of elemental hydrogen

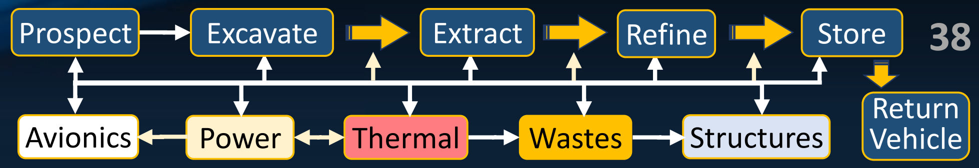
C_C [%wt]
Concentration of elemental carbon

C_S [%wt]
Concentration of elemental sulfur

NEO Composition

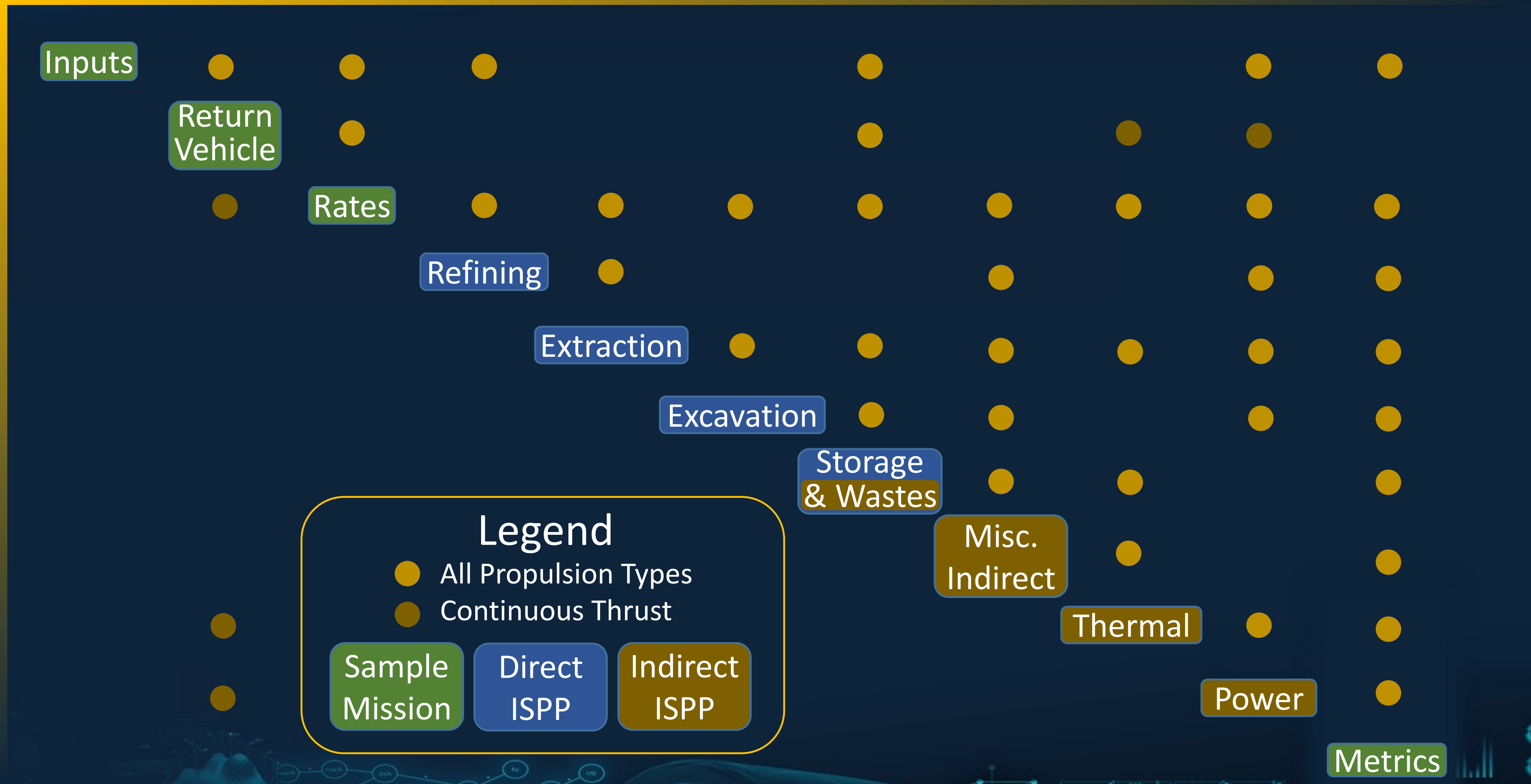
Conjecture 3:

The ten parameters represented here adequately capture the mission characteristics, solar radiation effects, and NEO composition.

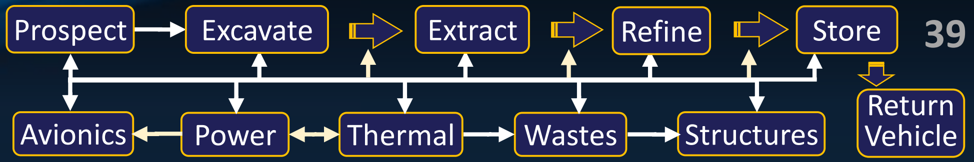


Design Structure Matrix

Introduction
Motivation
Methodology
Implementation
Qualitative
Quantitative
Experiment 1
Experiment 2
Conclusions



Inputs by Type



Input Handling: Python keyword arguments, or CSV batch reader

Primary

Driving factors

- $PROP\_TYPE$ — Chemical species to be produced by SoS
- Δv_{RT} [km/s] — change in velocity from NEO to LEO
- t_{STAY} [days] — Time between NEO arrival and departure
- D_{min} [AU] — Min. distance from sun during mission
- D_{max} [AU] — Max. distance from sun during mission
- t_{PERIOD} [hr] — Period of NEO rotation about its axis

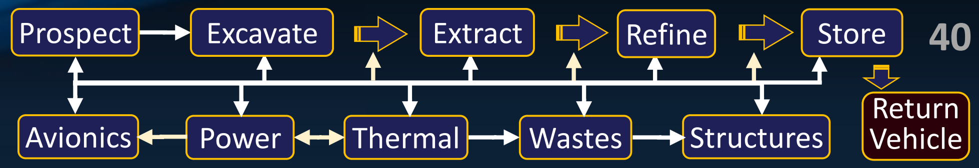
Secondary

Options & tuning factors

- C_H [%wt] — Concentration of elemental hydrogen
- C_C [%wt] — Concentration of elemental carbon
- C_S [%wt] — Concentration of elemental sulfur
- $CONC$ — Boolean switch: concentrator / lamp
- m_{PAY} [kg] — Mass of payload to be returned to LEO
- $OVERBURDEN$ — Proportion of mass excavated that isn't ore
- $MARGIN$ — Proportion of addl. mass at SoS level
- $OVERSIZE$ — Multiplier on prop. demanded quantity
- $REDUNDANT$ — Integer count of subsystem strings

- Override default values
- Option flag/switches
- High level modifiers

Propellant to Return



Return Vehicle Module: single rocket stage sized to find propellant required

Propellant	I_{sp}[s]	m_{eng}[kg]	P_{eng}[W]	η_{eng}[%]	Comparable Engine	
Hydrogen	3000 s	500 kg	100 kW	70% eff.	Ad Astra VASIMR VF-200	[4,5]
Water	270 s	118 kg	480 kW	50% eff.	TransAstra Omnivore @ 1850 K	[6]
Hydrolox	460.1 s	230 kg	mix 5.7		Aerojet Rocketdyne RL10C-3	[3]
Methalox	362 s	250 kg	mix 3.4		Avio Vega M10	[2]

Bare dry mass sized based upon Mass Estimating Relations given by Akin [1]

Δv = 5000 m/s
m_{PAY} = 2000 kg
30% mass contingency

Propellant	Bare Dry [kg]	m_{PROP}[kg]
Hydrogen	5178 kg	1396 kg
Water	4557 kg	38616 kg
Hydrolox	1872 kg	8248 kg
Methalox	1644 kg	11822 kg

- Spherical tanks with connecting frustums, plus electronics
- Solar panels (Hydrogen) & solar concentrator (Water) sized via Power Module, none for impulsive thrust
- Radiators for excess heat sized by Thermal Module

HoneyBee: 4714 kg (reported) vs. 4941 kg (0% cont.)
Δv = 290 m/s, m_{PAY} = 10^5 kg, I_{sp} = 335 s [6]

[1] D. L. Akin, "Mass Estimating Relations," Sep. 17, 2019,
[2] Avio, "VEGA E: M10 Motor," *Avio.com*, Aug. 2018.
[3] Aerojet Rocketdyne, "RL10 Propulsion System," Mar. 2019.
[4] F. Chang Diaz *et al.*, "An Overview of the VASIMR ® Engine," Jul. 201
[5] F. Chang Díaz and E. Seedhouse, "The VASIMR® Nuclear-Electric …"
[6] J. C. Sercel, et al. "Stepping stones:…", Mar. 2018,

Rate Adjustment

Rates Module: Adjust mass flow of propellant, find NEO insolation properties

Irradiation

Sunlight reaching NEO

- 1360.8 W/m^2 @ 1 AU, solar min [1]
- Inverse square law to scale with heliocentric distance

Mass Flow

Average demanded propellant

- Increase non-limited to stochiometric
- Useful time adjustment
  - Light & Dark operation factors
  - Deployment & checkout time
- Oversize – mult. factor option

NEO Temperature

Average expected NEO surface temperature

- Radiative equilibrium temperature, constant sunlight assumed
  - Absorptivity (0.982)
  - Emissivity (0.9)
  - Beam Param (1.8)
  - Area Ratio (1/4: sphere)
- Ignored diurnal cycle variation

Values for min. & max. heliocentric distance computed

[1] Kopp and Lean, 2011. DOI: 10.1029/2010GL045777

Refining

Introduction
Motivation
Methodology
Implementation
Qualitative
Quantitative
Experiment 1
Experiment 2
Conclusions

Refining Module: convert volatiles (H_2O & CO_2) into consumables (propellant)

MIT HabNet sizing equations & tuning factors used as baseline

- Added temperature states, to track heating & cooling
- Replaced tanks with rubberized ASME BPVC code
- Added stoichiometry checks & a few flow sensors

Acidic Electrolyzer

Split water across proton exchange membrane

- Multiple instances of fixed cell
- Variable casing size & tank instances
- State temperatures for hydrogen dryer and heat exchanger heat/cool
- Molar & mass species flow rates
- Pump included

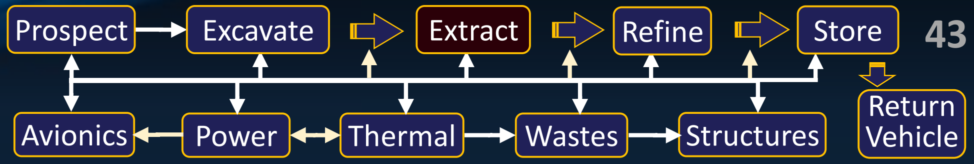
Sabatier Reactor

Methane from carbon dioxide and hydrogen

- Multiple instances of fixed channel
- Variable piping & tank instances
- State temperatures for chamber and ‘phase separator’ used for heat/cool
- Molar & mass species flow rates

[1] Do, 2016. “*Towards Earth Independence-Tradespace …*”
[2] Schrenk, 2015. “*Master Thesis Development of an ISRU…*”

Extraction



Extraction Module: evolve volatiles (H_2O & CO_2) from NEO ore

Thermal Vacuum

Bake out volatiles in vacuum chamber

- Batch heated – size volume
  - Linear temperature ramp used
  - Takt time vs. ore per batch
- Walls: nested tank instances
- Heating Demand
  - Specific heat: ore itself
  - Sublimation: volatiles
- Cooling Demand
  - Specific heat: volatiles

Sorbent Beds

Separate SO_2 from H_2O & CO_2, then them too

- Thermal Cycling
  - Specific heat: volatiles
  - Sets stage temperatures
- Not yet sized: chamber, where to sit

Excavation

Excavation Module: extract NEO ore from bulk NEO

Corer

Cutting head that can also take samples

- Multiple instances of fixed size
  - Cores per bit drilled
  - Kerf dust vs. soild removed
  - Cutting energy per volume
- Cutting energy per volume

Robotic Arm

Means to reposition cutting head

- Multiple Instances of fixed size
  - one per group of corers
- NASA InSight arm, borrowed not sized

Storage & Wastes

Storage Module: all mass input stored after processing; chill then put in tank

Chiller

Heat removed for cryogenic storage

- Cooling Requested
  - Pulls last stage temperature
  - Cools to vaporization or sublimation point for material

Chemical	T_{in}[K]	T_{store}[K]
Oxygen	358 K	90 K
Carbon Dioxide	358 K	194 K
Sulfur Dioxide	333 K	263 K
Water	358 K	273 K
Methane	363 K	111 K
Hydrogen	358 K	20 K

Tankage

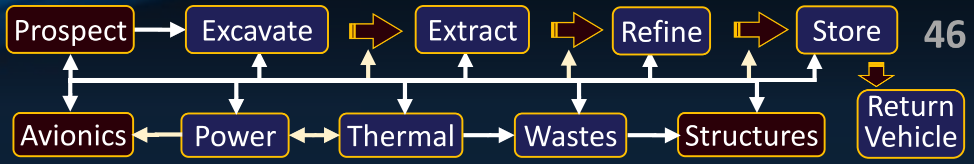
Rubberized ASME BVPC Instance

- Pressure vessel, thickness to code Sized to 1 atmosphere, except for granular solids
- Densified propellant used to compute storage volume

- **Overburden** is the component of regolith that is not considered to be ore; regolith that is excavated but not subject to extraction.
- **Tailings** are the portion of ore that is left after volatiles have been extracted.

- **Byproducts** are substances produced while refining volatiles that are not considered consumables in their own right.
- **Excess** is consumables produced beyond the quantity demanded by the customer.

Miscellaneous



Miscellaneous: Avionics – command & communications to coordinate SoS
Material Handling – move masses between equipment
Prospecting – locate ore in NEO, usually from orbit
Structures – bear mechanical loads, control attachment to NEO

Auger

Granular solid material handling

Digitized scaling from MIT HabNet; sized at 1 rpm, too small DIA otherwise

Pump

Fluids material handling

Multiple instances (10 kg ea.), taken from MIT HabNet Electrolyzer

Unsized Functions

Fairly high fairly high values for system mass contingencies (30%) and overall SoS mass margin (30%) by default, to compensate.

MARGIN
Proportion of addl. mass at SoS level

CONTINGENCY
Proportion of addl. mass at system level

Sized overall mass of SoS nearly doubles as a result.

[1] Do, 2016. "*Towards Earth Independence-Tradespace …*"
[2] Schrenk, 2015. "*Master Thesis Development of an ISRU…*"

Thermal Mgmt.

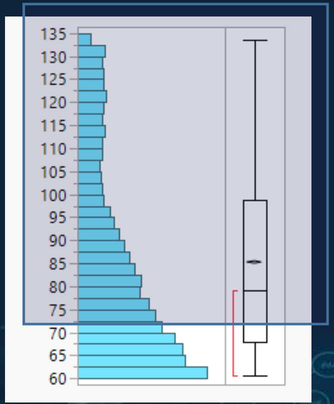
Thermal Module: heat & cool to keep process equipment at good temperature

Radiators

Cooling through radiation for heat rejection

- Radiation balance per area
  - Solar Irradiation
  - NEO with view-factor (subtract)
  - Fin efficiency
- Cooling divided by de-rated flux

Cooling Mass Penalty [kg/kW]



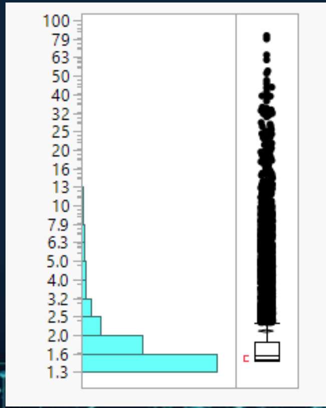
BVAD:
72 kg/kW
> PMP >
190 kg/kW

IR Lamps

Heating of ore through artificial radiation

- Multiple Instances of flexible size
  - Mainly scales with tube length
- Imperfect reflector coating used
  - Un-reflected light becomes cooling load to be rejected

Heating Mass Penalty [kg/kW]



Anderson et al., 2015. "Life Support Baseline Values and Assumptions Document" (BVAD)

Power Mgmt.

Power Module: electrical generation & storage

Photovoltaic Cells

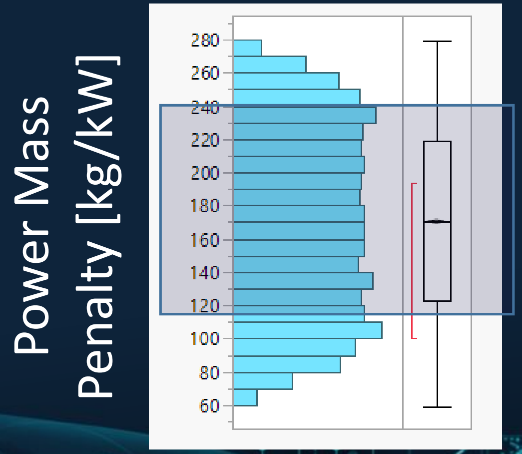
Electricity from solar irradiation

- Uprate demand to account for dark operation & charging inefficiency
- Derating incident irradiation
  - Solar Irradiation
  - Temperature (not cooled, in radiative equilibrium)
  - Degradation during mission
  - Losses: Cell, Assembly, Cosine
- Power divided by de-rated flux gives area, mass per area used

Li-Ion Batteries

Secondary battery cells for operation in dark

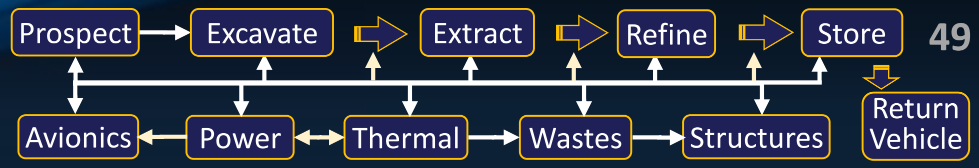
- Multiple instances of fixed size
- Energy storage sized for average dark power during dark portion of NEO period



BVAD:
113 kg/kW
> PMP >
239 kg/kW
In LEO

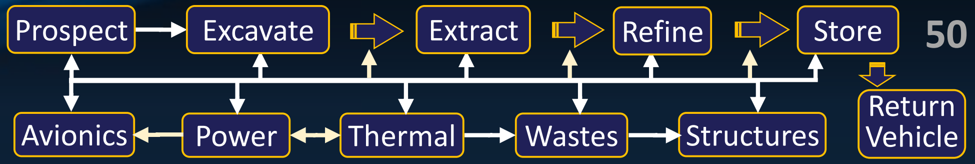
Anderson et al., 2015. “Life Support Baseline Values and Assumptions Document” (BVAD)

Metrics: Mass



- Total Mass of Processing Equipment (m_{ISPP}) [kg]
  - Aggregate mass of all systems in ISPP plant; excludes return vehicle
- Mass Fraction: portions of m_{ISPP}, before mass margin (∑ = 100%wt)
- Mass Payback Ratio (MPR) [N.D.]
  - $MPR \equiv \frac{\text{mass of resources}}{\text{mass of equipment}} = \frac{m_{fuel}+m_{ox}+m_{samp}}{m_{ISPP}}$; $MPR_{PROP} = \frac{m_{fuel}+m_{ox}}{m_{ISPP}}$
- Useful Regolith Proportion ($UseReg$) [%wt] – NEW
  - $UseReg \equiv \frac{\text{mass of resources}}{\text{mass of regolith processed}} = \frac{m_{fuel}+m_{ox}+m_{samp}}{m_{reg}}$
- Useful Volatiles Proportion ($UseVols$) [%wt] – NEW
  - $UseVols \equiv \frac{\text{mass of propellant}}{\text{mass of volatiles evolved}} = \frac{m_{fuel}+m_{ox}}{m_{H_2O}+m_{CO_2}+m_{SO_2}}$

Metrics: Energy Use



- Total Power (P_{ISPP}) [We], Heating ($Q_{H,ISPP}$) [Wt], Cooling ($Q_{C,ISPP}$) [Wt] demand of ISPP plant (direct & indirect), excluding return vehicle
- Energy Use Fractions: portions of total energy use ($\sum$ = 100%) – NEW
  - Power, Heating, & Cooling aggregated – double counting from transformations included
- Specific Energy Intensity (SEI) [J/kg] – NEW
  - $$SEI \equiv \frac{\text{rate of energy use}}{\text{rate of propellant production}} = \frac{P_{ISPP} + Q_{H,ISPP} + Q_{C,ISPP}}{\dot{m}_{fuel} + \dot{m}_{ox}}$$
- Power Mass Penalties (PMP) [kg/kW]
  - $$PMP \equiv \frac{\text{mass of system handling energy}}{\text{demanded energy use capacity}} = \frac{m_{POW}}{P_{ISPP}}, \frac{m_{HEAT}}{Q_{H,ISPP}}, \frac{m_{COOL}}{Q_{C,ISPP}}$$
- Mass Throughput (f) [1/day (Earth)]
  - $$f \equiv \frac{\text{mass of matter processed}}{\text{mass of equipment} * \text{time to process}}; f = \frac{m_{PROP}}{m_{ISPP} * t_{PROD}}$$

Q5.1: Varying Mission Parameters

Cases: 275

Introduction
Motivation
Methodology
Implementation
Qualitative
Quantitative
Experiment 1
Experiment 2
Conclusions

Experiment 1 (E1):
Vary the six primary input parameters associated with the mission ($\Delta v_{RT}, t_{STAY}, PROP\_TYPE$) and solar irradiation ($D_{SUN,min}, D_{SUN,max}, t_{PERIOD}$), with constant sample mass and composition.

Design of Experiments	Variable	Units	Min.	Nom.	Max.	
Change in velocity required to (NEO to LEO)	Δv_{RT}	m/s	500	4,646[5]	8,000	0.5 – 3.0 km/s [1] 3.8 – 27 km/s [5]
time on station at NEO	t_{STAY}	days	30	100	365	0.1 – 100 years [1]
Minimum solar distance of NEO during mission	D_{min}	AU	0.75	0.9633[3]	1.2	0.75 – 1.2 AU [1]
Maximum solar distance of NEO during mission	D_{max}	AU	0.85	1.4159[3]	1.45	0.85 – 1.45 AU [1]
Period of the NEO	t_{PERIOD}	hours	2.5	7.6326[3]	24	1 – 9.5 day^{-1} [2]
Propellant Type	$PROP\_TYPE$	Steam	Hydrogen	Hydrolox	Methalox	**Cases: 275**

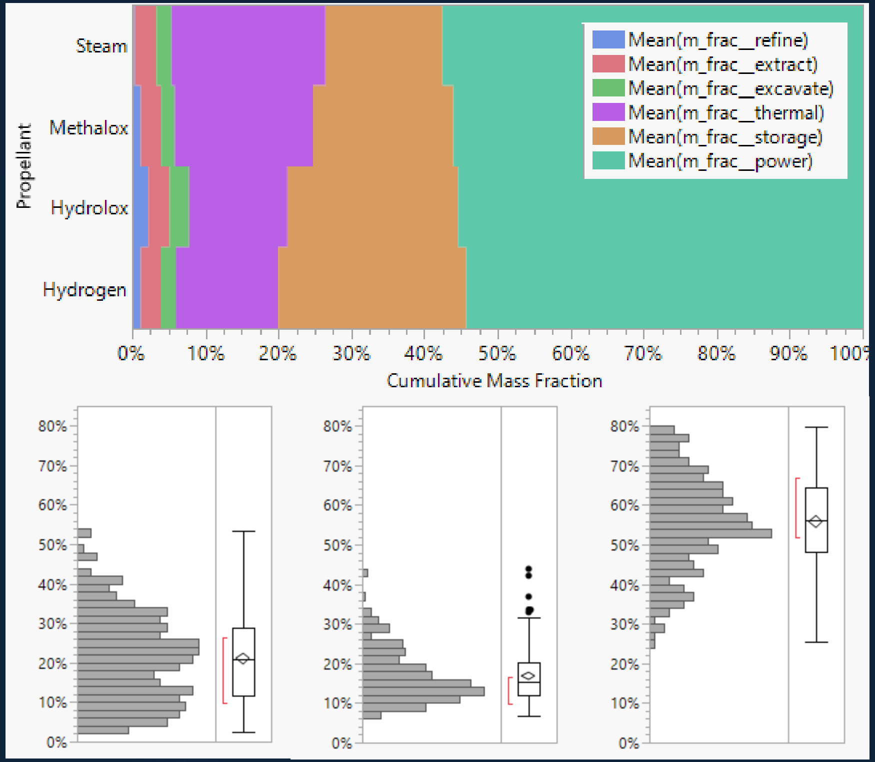
Hypothesis 5.1:
If sized ISPP plant mass sensitivity to primary inputs about NEO orbital characteristics is analyzed, then the change in velocity to return (Δv_{RT}) [km/s] will have the greatest contribution to variability.

[1] (Jedicke et al. 2018)
[2] (Pravec et al. 2008)
[3] Ryugu in (Scheeres et al. 2019)
[4] Orgueil Meteorite (Metzger et al. 2019)
[5] Delta-v for Rendezvous (Benner 2018)

E1: Relative System Sizing

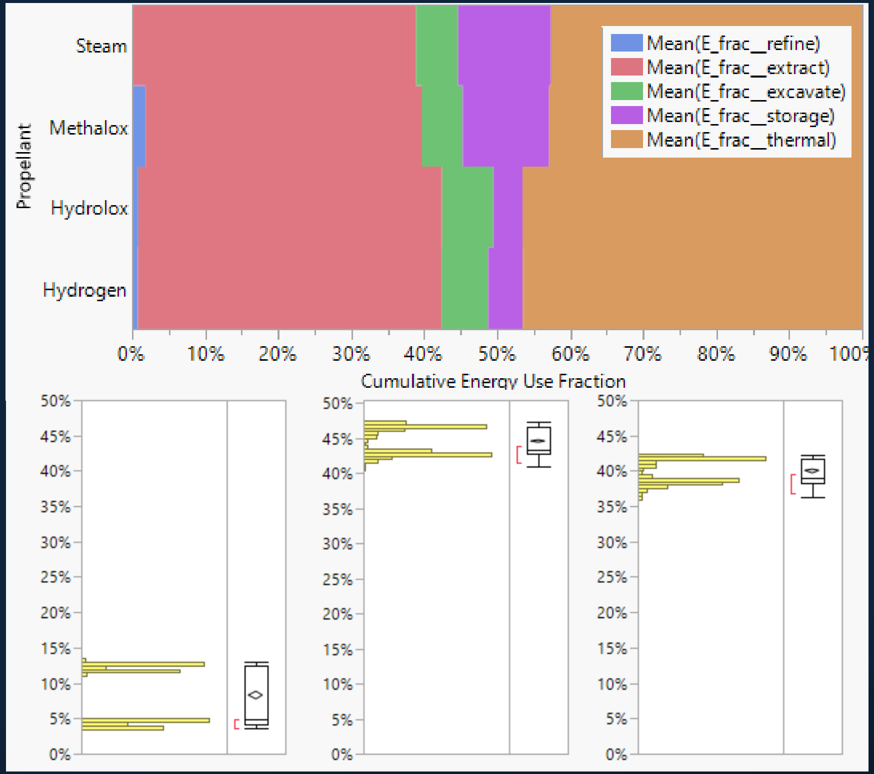
Cases: 275

Mass Fractions



Storage, Thermal, & Power

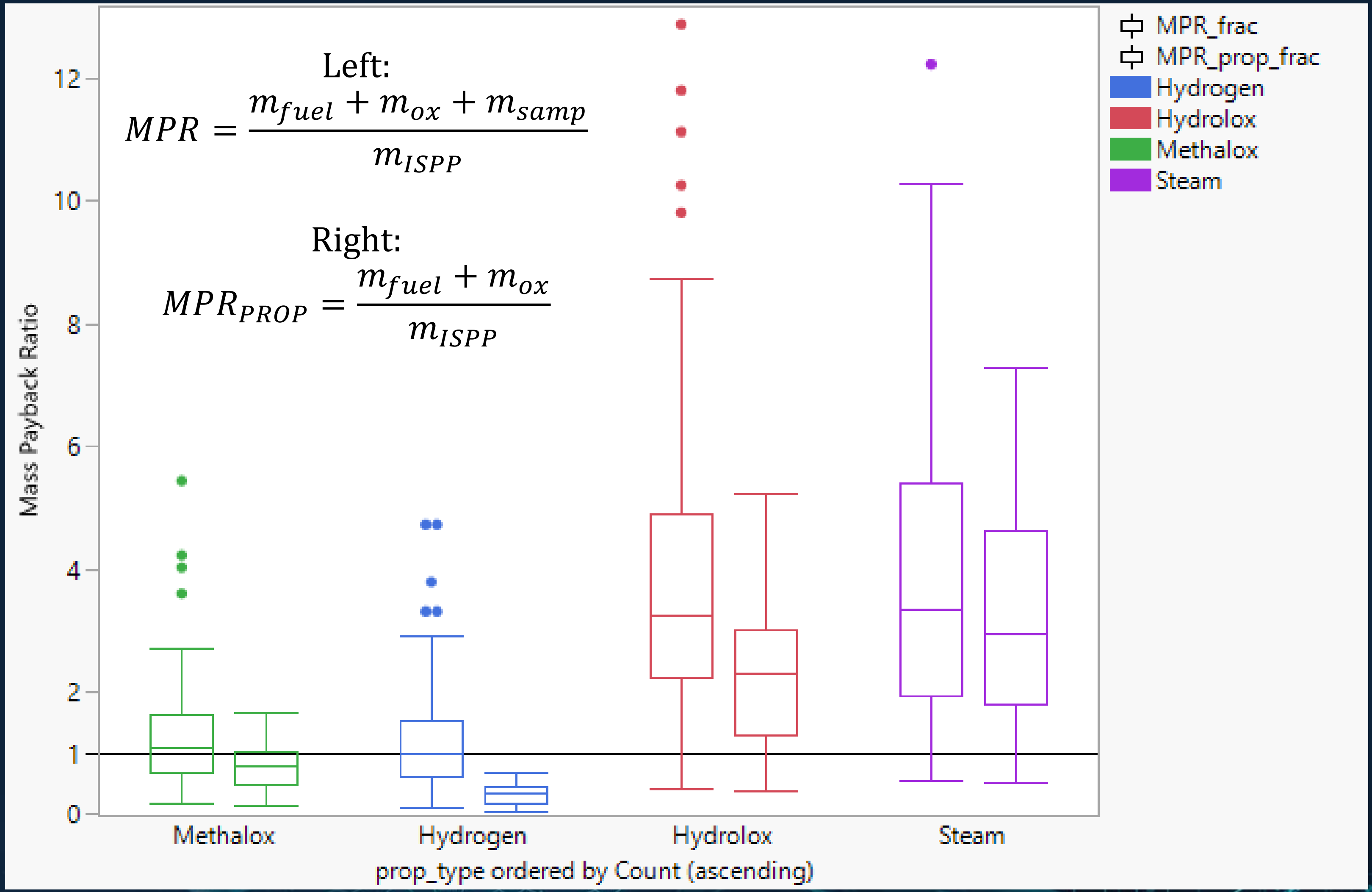
Energy Use Fractions



Storage, Thermal, & Extraction

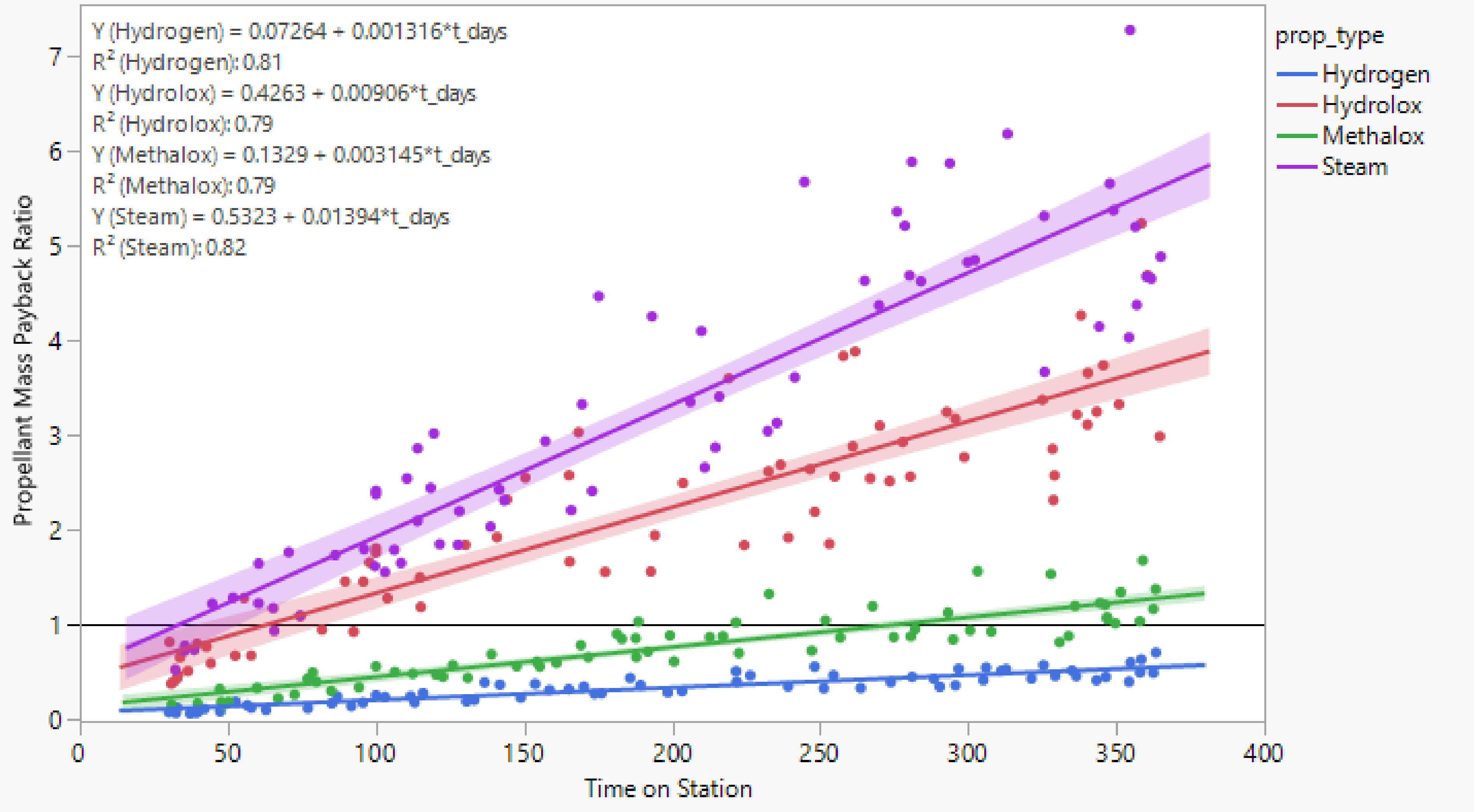
E1: Mass Payback Ratio

Cases: 275



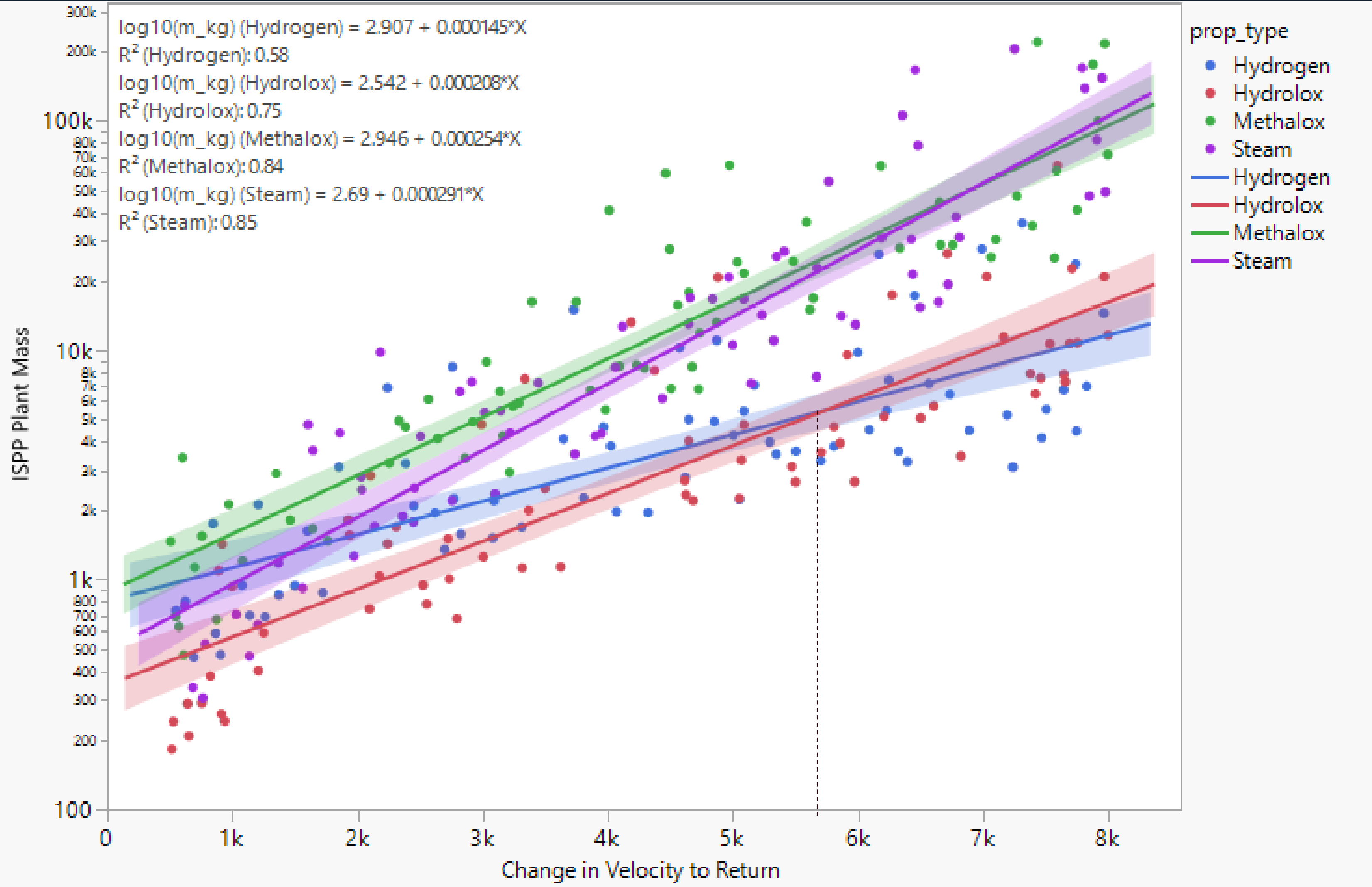
E1: Mass Payback Ratio

Cases: 275



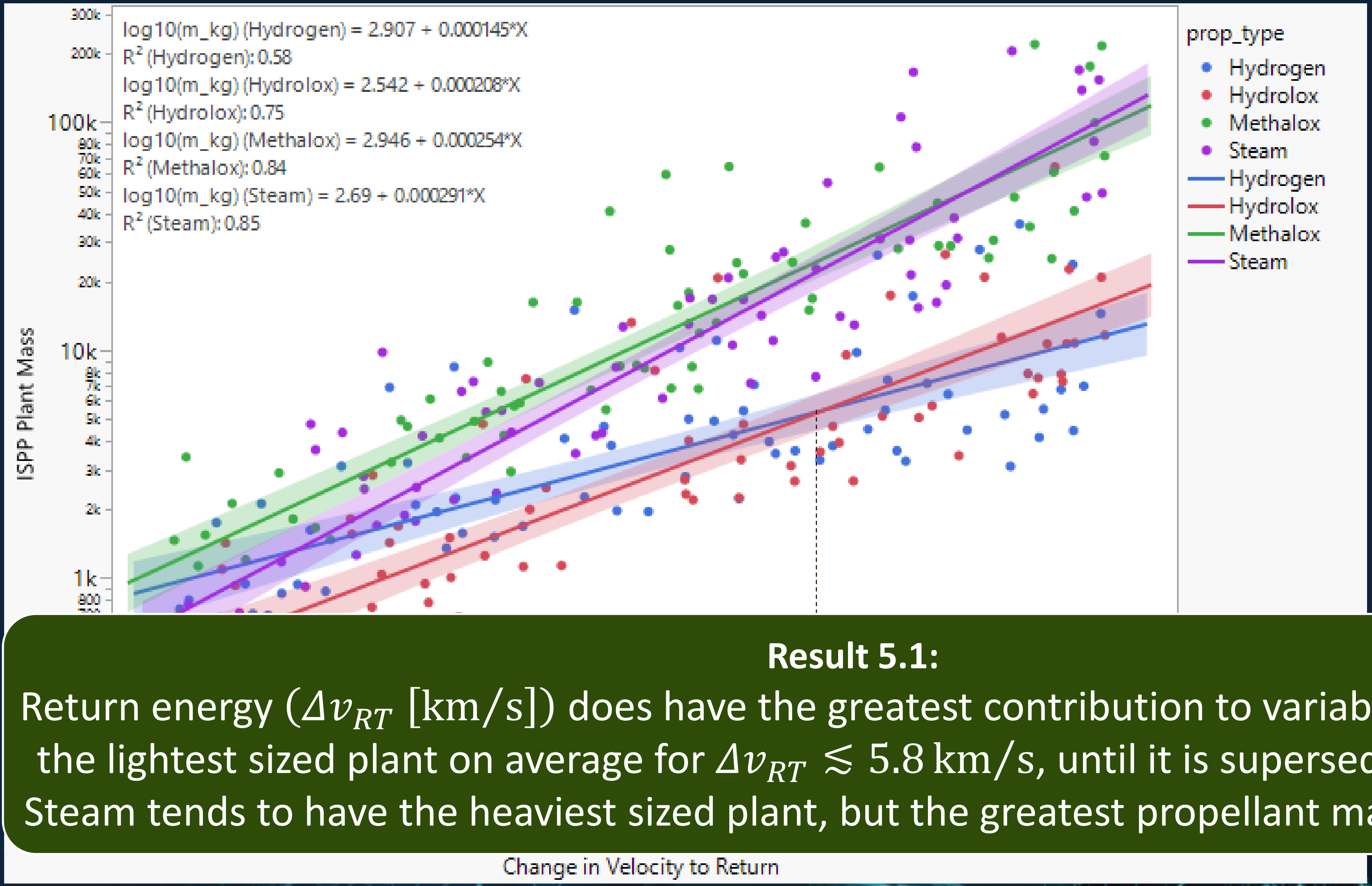
E1: Concept Scaling

Cases: 275



E1: Concept Scaling

Cases: 275



Result 5.1:

Return energy (Δv_{RT} [km/s]) does have the greatest contribution to variability. Hydrolox has the lightest sized plant on average for $\Delta v_{RT} \lesssim 5.8$ km/s, until it is superseded by hydrogen. Steam tends to have the heaviest sized plant, but the greatest propellant mass payback ratio.

Q5.2: Varying NEO Composition

Cases: 13,342

Experiment 2 (E2):
Vary payload mass (m_{PAY}) and composition ($C_C, C_H, C_S, OVERBURDEN$)
in addition to other mission and solar irradiation related parameters

Design of Experiments	Variable	Units	Min.	Nom.	Max.
Change in velocity required to (NEO to LEO)	Δv_{RT}	m/s	500	4,646[5]	8,000
time on station at NEO	t_{STAY}	days	30	100	365
Minimum solar distance of NEO during mission	D_{min}	AU	0.75	0.9633[3]	1.2
Maximum solar distance of NEO during mission	D_{max}	AU	0.85	1.4159[3]	1.45
Period of the NEO	t_{PERIOD}	hours	2.5	7.6326[3]	24
Propellant Type	$PROP\_TYPE$	Hydrogen	Steam	Hydrolox	Methalox
Mass of samples returned from NEO	m_{SAMP}	kg	100	2,000	10,000
Regolith removed that is overburden, not ore	$OVERBURDEN$	%wt	0%	0%	90%
Mass fraction of NEO ore that is carbon atoms	C_C	%wt	0.5%	3.22%[4]	15%
Mass fraction of NEO ore that is hydrogen atoms	C_H	%wt	0.5%	2.02%[4]	5.49%
Mass fraction of NEO ore that is sulfur atoms	C_S	%wt	0%	5.25%[4]	10%

0.5 – 3.0 km/s [1]
3.8 – 27 km/s [5]

0.75 – 1.2 AU [1]
0.85 – 1.45 AU [1]
1 – 12 day^{-1} [2]

55%wt CO_2
98%wt water
20.6%wt SO_2

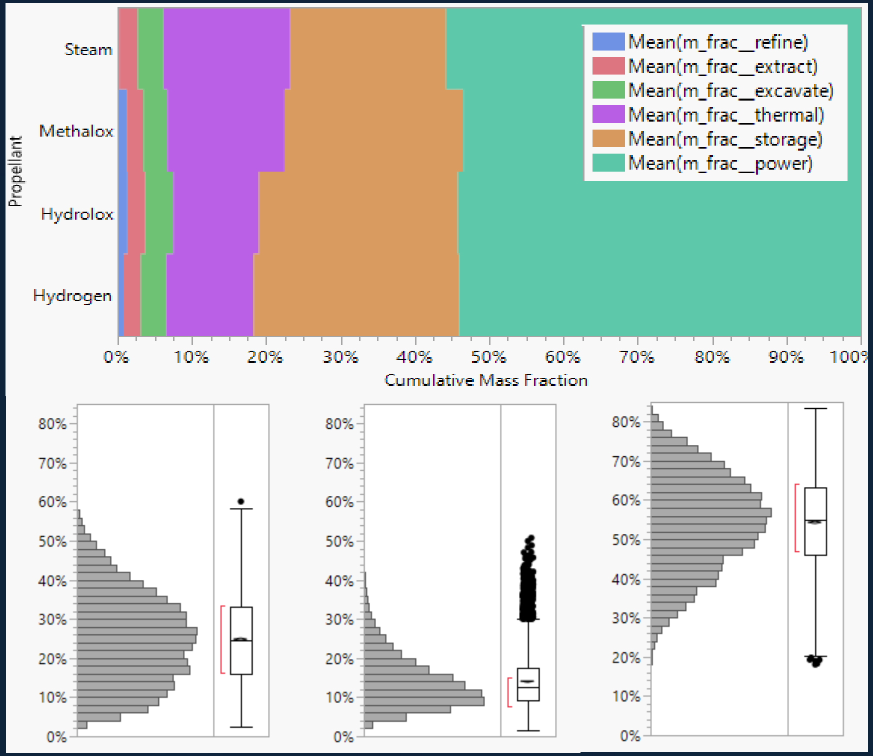
Hypothesis 5.2:
If sized ISPP plant mass sensitivity to NEO composition is analyzed,
then the availability of water will have the greatest contribution to variability.
When uncertainty in composition is considered, Methalox concepts are anticipated to be more robust.

[1] (Jedicke et al. 2018)
[2] (Pravec et al. 2008)
[3] Ryugu in (Scheeres et al. 2019)
[4] Orgueil Meteorite (Metzger et al. 2019)
[5] Delta-v for Rendezvous (Benner 2018)

E2: Relative System Sizing

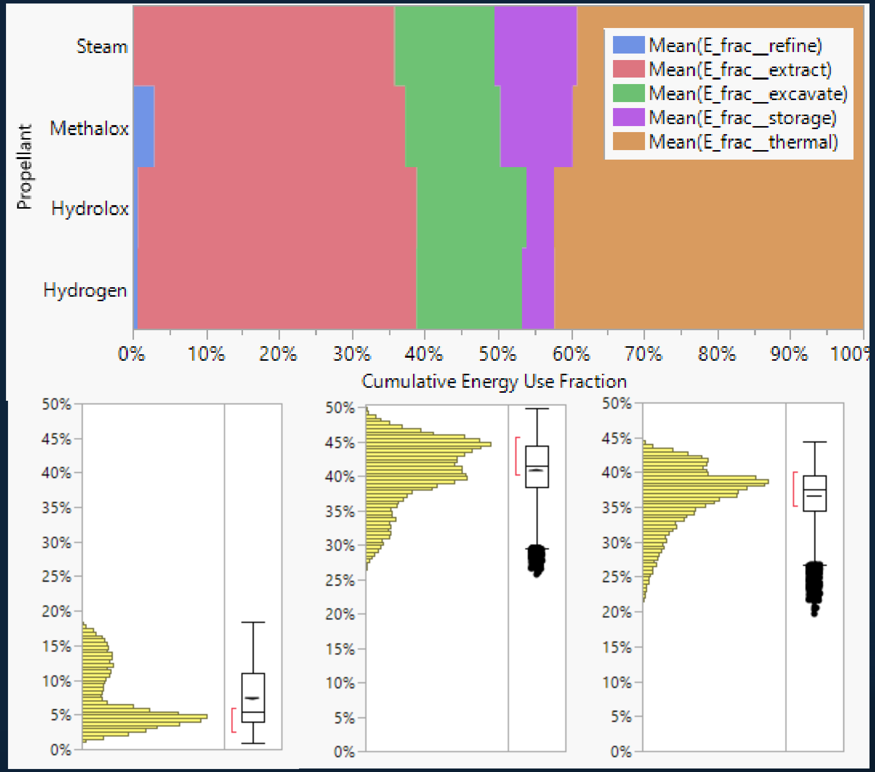
Cases: 13,342

Mass Fractions



Storage, Thermal, & Power

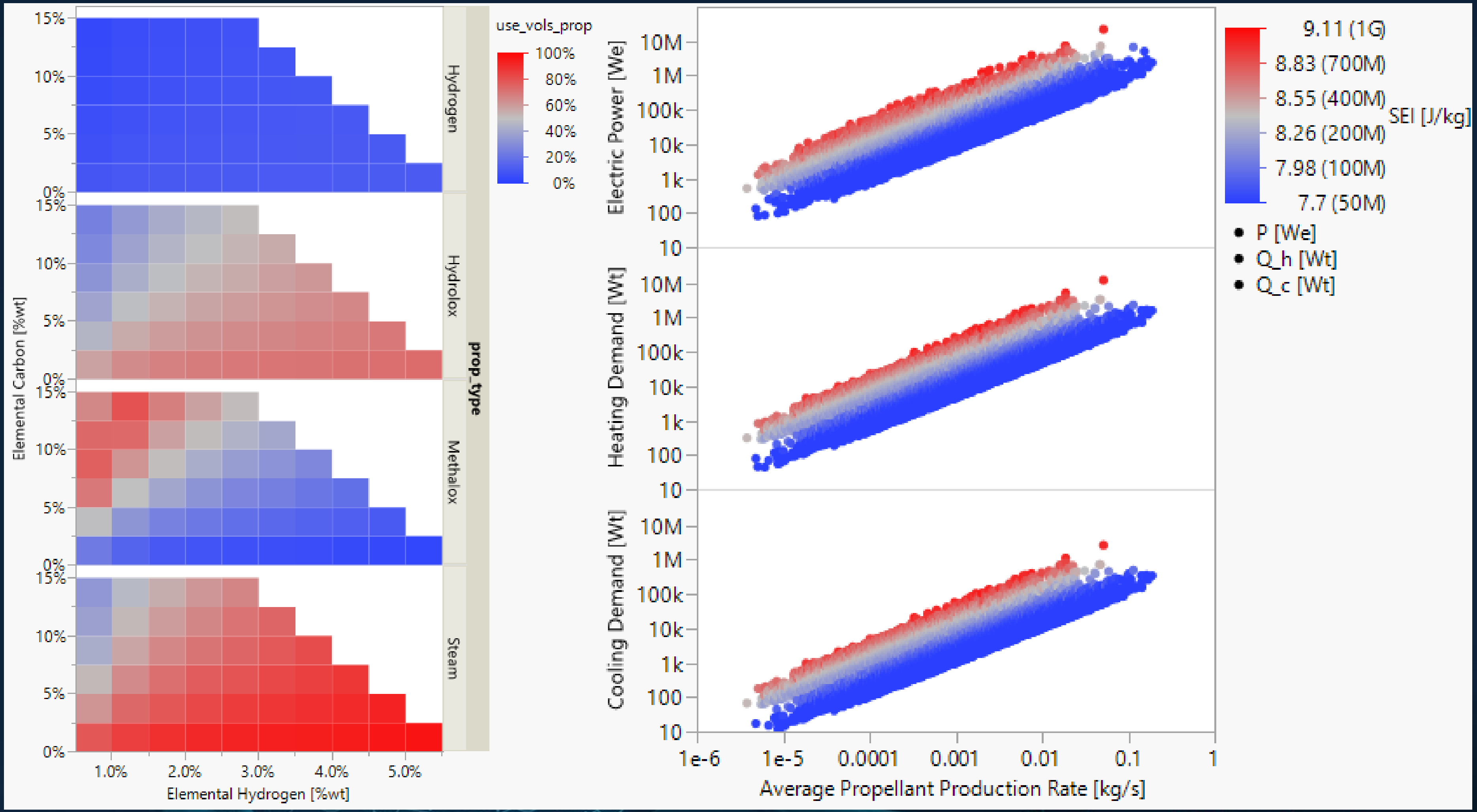
Energy Use Fractions



Storage, Thermal, & Extraction

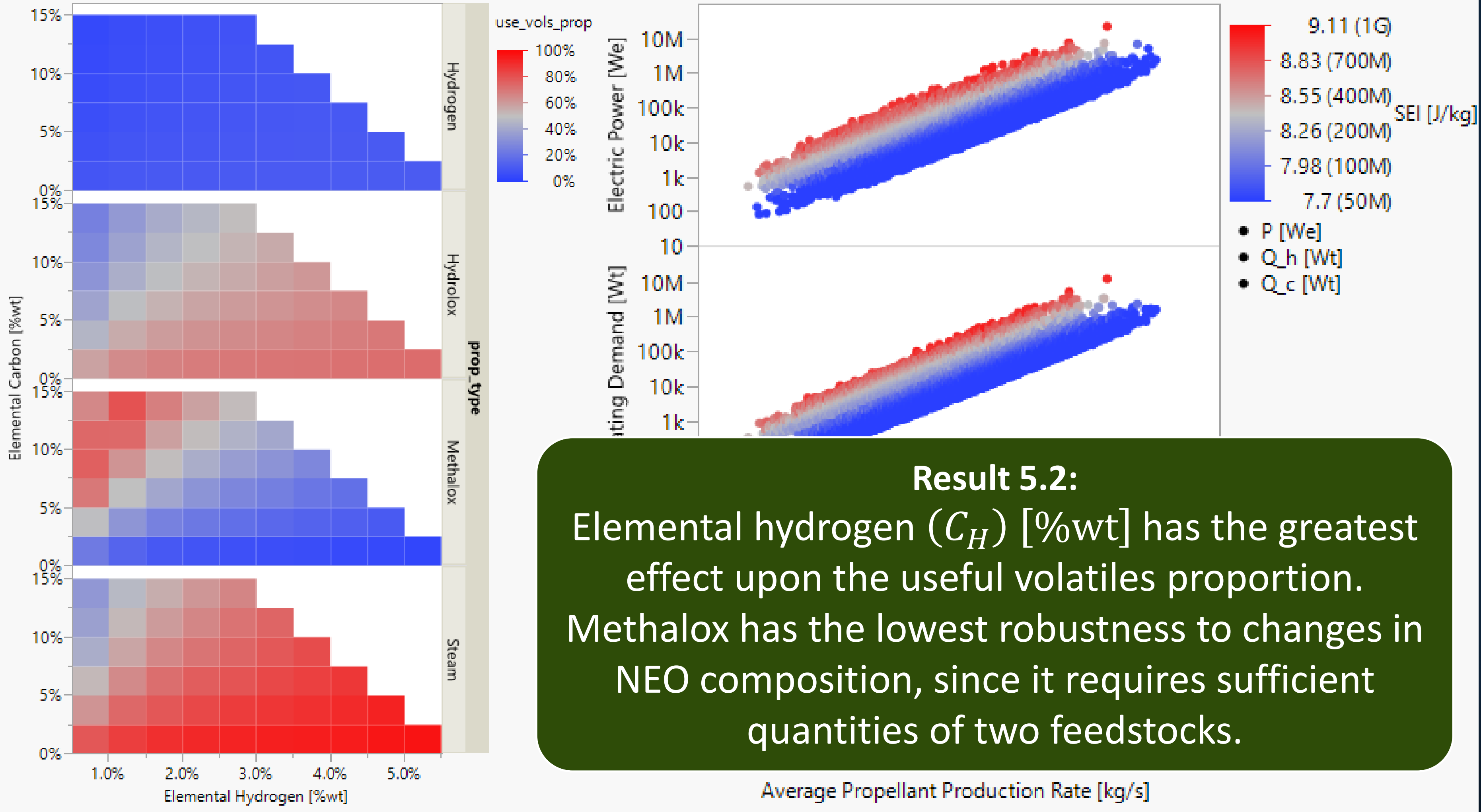
E2: Composition Effects

Cases: 13,342



E2: Composition Effects

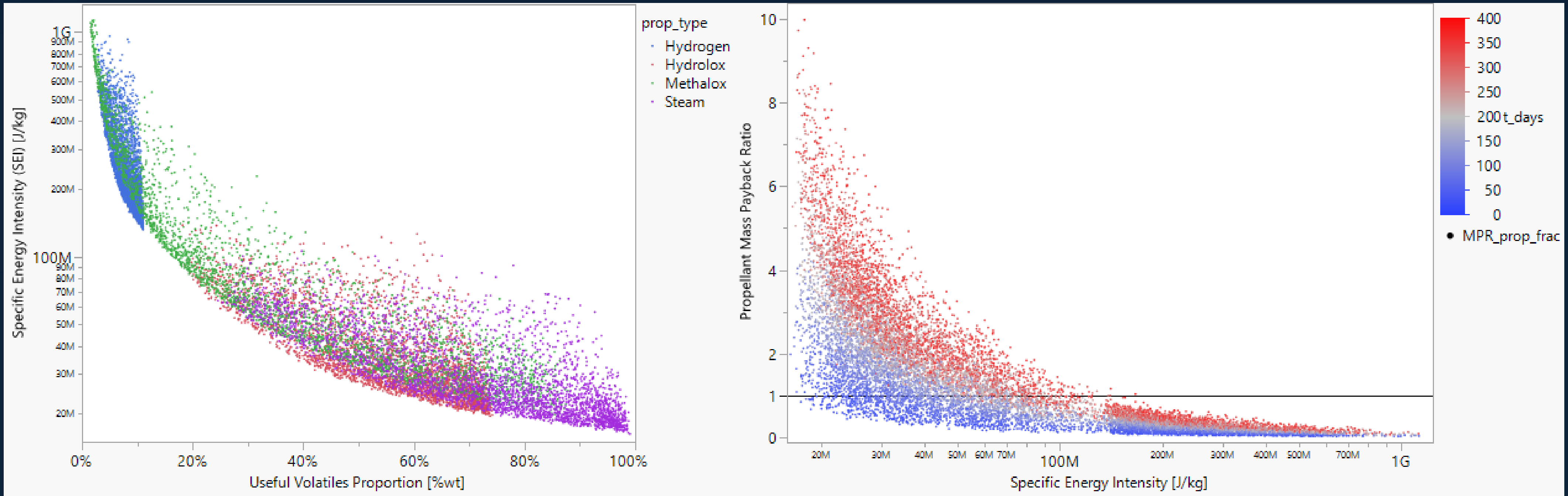
Cases: 13,342



Result 5.2:
Elemental hydrogen (C_H) [%wt] has the greatest effect upon the useful volatiles proportion. Methalox has the lowest robustness to changes in NEO composition, since it requires sufficient quantities of two feedstocks.

E2: Specific Energy Intensity (SEI)

Cases: 13,342



Conjecture 5:

Increasing the useful volatiles proportion drives the specific energy intensity, which in turn drives propellant mass payback ratio.

Extraction system performance drives SoS sizing due to large energy demands.

Research Objective (Achieved)

Introduction
Motivation
Methodology
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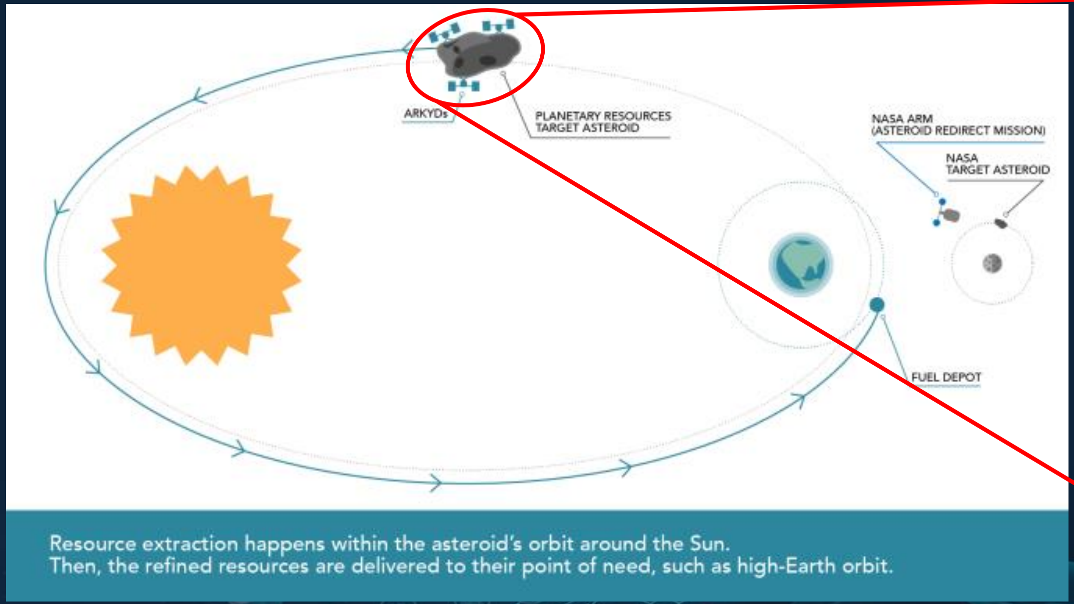
Review Goals
Contributions
Future Work

A methodology has been developed to compare on equal footing In-Situ Resource Utilization (ISRU) System of System (SoS) concepts involving Near Earth Objects (NEOs).

Case Study is the conceptual design and sizing of a sample return mission to a 'primitive' Near Earth Object (NEO), involving the use of In-Situ Propellant Production (ISPP) to enable return to Low Earth Orbit (LEO).



HoneyBee Robotics Spider

Planetary Resources, 2015. "Safe and Efficient Asteroid Mining".
Zacny, Kris 2017 "Asteroid ISRU" SBAG, Tuscon, AZ,

Research Question Summary

Research Question 1: Systematic comparisons of design concepts	**Conjecture 1:** Qualitative: Morphological matrix & TRLs; Quantitative: Sizing code, parameters & metrics
Research Question 2: Most feasible NEO ISPP concept from TRLs	**Result 2:** Hydrolox 'HO' concept should act as a good baseline
Research Question 3: Parameters to describe NEO ISPP for sample return	**Conjecture 3:** Δv_{RT}[km/s], m_{SAMP}[kg], D_{min}[AU], D_{max}[AU], C_C[%wt], C_H[%wt], C_S[%wt], t_{STAY}[days (Earth)], t_{PERIOD}[hours (Earth)], $PROP\_TYPE$
Research Question 4: Most feasible application for NEO ISRU?	**Conjecture 4:** **S**ample return from **N**ear earth object with **I**n-situ **P**ropellant production **T**echnology demonstrator (SNIPT)
Research Question 5: Choice of produced propellant trade study	**Result 5.1, Result 5.2, & Conjecture 5:** Hydrolox lightest $\Delta v_{RT} \lesssim 5.8$ km/s, then hydrogen but $MPR_{PROP} < 1$; C_H [%wt] → $UseVols$ [N.D.] → SEI[J/kg] → MPR_{PROP}[N.D.]

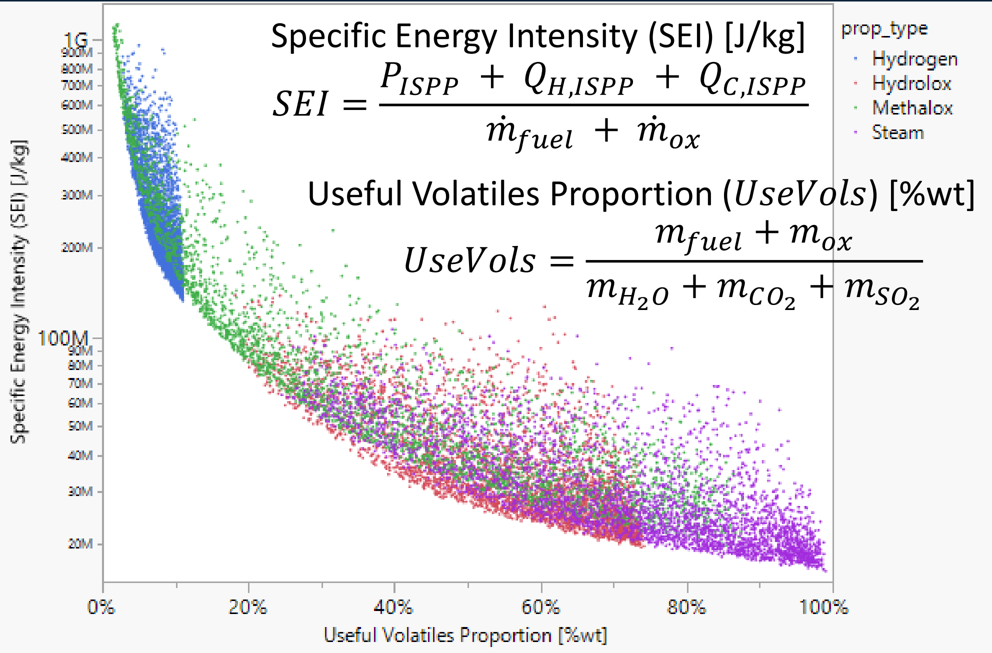
Novel Contributions

- Introduction
- Motivation
- Methodology
- Implementation
- Conclusions
  - Review Goals
  - Contributions
  - Future Work

- Review of proposed NEO ISRU SoS concepts
- Idea for SNIPT mission proposal
- Morphological matrix of alternatives for NEO ISPP SoS design trades
- Proposed standardized terminology for NEO ISPP SoS options
- Baseline functionally complete NEO ISPP SoS concept, with reference mission
- Sizing code tied to morphological matrix
- Sizing code considering energy use for NEO ISPP SoS concepts
- Additional metrics to quantify performance of NEO ISPP SoS concepts, and identifying relationships between them
- Propellant trade study from ISRU perspective

Shaded Options: Microgravity TRLs

Task	Group	Category	Morphological Options						Null?
Sample Return	Integration	Separation	Single Unit (None)	Detachable Modules	Subsequent Missions	Swarming Craft			
		Redunancy	Single String (None)	Independent Strings	Cross-Strapped Strings	Multiple Craft			
	Return Vehicle	Propulsion	Chemical Reaction (liquid)	Solar Thermal	Nuclear Thermal	Electrothermal	Electromagnetic	Ion Thruster	
		Propellant	Water/Steam	Hydrogen	Hydrolox	Methalox			
		Chamber Reaction	Fuel Rich	Stoichiometric	Oxidizer Rich				N/A
		Return Type	Whole SoS	Partial / Some Systems	Return Vehicles				
Direct ISRU	Prospecting	Local Observations	Passive Observation	Active Observation	Seismic Survey	Orbit Gravimetry			
		Wave Type	Far Infrared / Thermal	Near Infrared	Visible Light	Radar	Sound / Mechanical	Subatomic Particles	N/A
		Sampling	Kinetic Penetrator (smart)	Impactor (dumb)	Excavate (automated)	Touch & Go (TAGSAM)	Skyhook / Harpoon		N/A
	Excavation	Containment	Clamshell Enclosure	Synched Bag	Tube Sleeve	Localized Membrane			
		Cut Rock	Auger Bit	Corer	Percussive Drill	Optical Beam (spalling)	Jet (plasma)	Rotary Cutter	
		Powderize	Pneumatic Probes	Borehole Heating	Rip/Fracture	Cut Debris (kerf/spall)	Crush		N/A
		Sorting/Sizing	Filtration	Centrifugal (density)	Sieves				N/A
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Resistance (electrical)	Dielectric (microwave)	Jet (Heated)	Induction	
		Beneficiation	Centrifugal (Density)	Magnetic Separation	Electrostatic Separation	Molten Powderization	Reformer	Leachate (Chemical)	N/A
		Volatile Capture	Cold Trap (Deposition)	Condenser	Sorbents	Vacuum Distillation			
	Refining	Make Oxygen	Carbothermal Reduction	Split Water	Metal Electrolysis	Ionic Liquid Reduction			N/A
		Make Hydrogen	Acidic Electrolysis	Alkaline Electrolysis	Solid Oxide Electrolysis	Thermolysis (Heat)	Photocatalytic (Light)		N/A
		Crack Hydrocarbons	Reverse Water Gas Shift	Steam Reforming	Pyrolysis (Heat)	Thermal Oxidation (Burn)	Fluid Catalytic		N/A
		Make Methane	Fischer-Tropsch Process	Sabatier Process	Photocatalytic				N/A
		Quality Control	Process Monitoring	Output Check	Batch Quarantine				
	Storage	Medium	Cryogenic Liquid	Cryogenic Solid	Pressurized Gas	Granular Solid	Chemical	Gel	
		Insulation	Multi-Layer Insulation	Coatings (External)	Sun Shade / Sunshield	Body Lining (Internal)	Dewar / Vacuum Shell		
	Material Handling	Granular Solids	Mechanical Pusher	Auger / Screw Feeder	Pneumatics	Rotating Feeder ('Airlock')	Electrostatic		N/A
		Fluids (Liquid & Gas)	Pressure Fed (by Heating)	Jet (momentum transfer)	Pressure Differential	Flow Ionization			
		Work Input	Heating (Volume Increase)	Shaft Work (Pump)	Linear Actuator	Compressor (Pressure)	Reference Frame (Spin)		
Indirect ISRU	Avionics	Autonomy	Autonomous	Automated	Remote				
		Computation	Centralized	Distributed	String Isolated				
		Local Comms	Transmitted	Wired					
		Deep Space Comms	Powerful Radio (DSN)	Laser Link	Repeaters				
	Power	Electrical Generation	Concentrated Solar Power	Photovoltaic Cells	Thermal Gradient	Radioactive Decay (RTG)	Fission Reactor		
		Energy Storage	Batteries	Capacitors	Chemical / Fuel Cell	Thermal Mass			N/A
		Beam Transmission	Fiber Optics	Mirrors	Beamed Microwaves				N/A
	Thermal	Heating [Secondary]	Focused Sunlight	Light (lamp/laser)	Resistance (electrical)	Chemical Reaction			
		Cooling	Passive	Radiators	Barbecue Roll	Heat Storage	Sublimation		
		Heat Exchanger	Cold Plate	Finned	Tubular	Phase Change / Cycle			N/A
		Distribution	Water Loop	Refrigerant Loop	Heat Pipes	Peltier Effect (electrical)	Thermoacoustics		
	Wastes	Tailings & Overburden	Eject into Space	Storage/Reuse	Deposit in Source	Secure in Place			
		Byproducts & Excess	Vent into Space	Storage/Reuse	Inject into Source				
	Structures	Support Structure	Central Bus / Cylindrical	Truss / Space Frame	Panel / Stressed Skin	Floors / Support Decks	Inflatable		
		Positioning	RCS Thrusters	Inflatable Airbags	Harpoon / Anchor	Guy Wires / Tensegrity	Microspines / Claw	Friction with Excavator	
		Relative Motion	RCS Thrusters	Main Thrusters	Robotic Joints	Cable Tension	Internal Gas Jets	Reaction Wheels	
		Rotation Control	Selective Ablation	Thruster Pods	Orbital Nudging	Friction with Containment	Impactor		N/A



Trade Studies Enabled

Introduction
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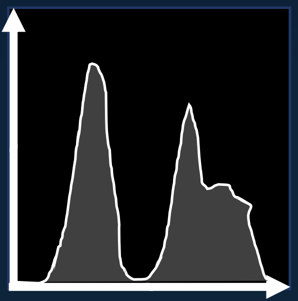
Review Goals
Contributions
Future Work

- Requirements Analysis – mission & destination
  - Comparing alternate NEO destinations (esp. Δv, aphelion, perihelion, composition)
  - Investigating changes in mission duration (esp. time on station)
  - Changes in readiness status (scheduled downtime, lesser operation in darkness)
  - Reserve capacity (oversize factor, redundant strings, mass contingency and margin)
- Propellant Customer / Return Vehicle Options
  - Propellant choice impacts upon ISPP SoS sizing (mass, energy use, complexity)
  - Impulsive vs. continuous thrust propulsion as a customer of ISPP
  - Sensitivity studies of ISPP sizing versus propulsion performance (specific impulse, mixture ratio, engine mass, power demand, cooling load)
- ISRU Option Trades
  - Processing high-grade ore deposits vs. homogenous low-grade regolith (overburden fraction, elemental composition, different cutting energies)
  - Comparing volatile yield between NEO of different elemental composition
  - 'Optical mining' with concentrated sunlight vs. electric heat lamps
  - Varying storage tank materials and storage temperature

Recommended Future Work

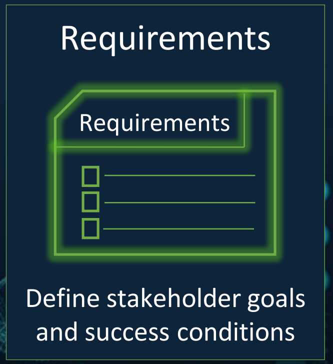
- Improve Sizing Code
  - Size rest of options within for selected concepts
  - Add other options within a category for comparison
  - Tweak to enable more involved trade studies
  - Probability density functions for parameters using Bayesian methods



- Technology Identification Evaluation and Selection (TIES)
  - Formal Technology Readiness Assessment
  - Compatibility matrix inclusion
  - Cost modeling (project planning)

NASA Mars DRA 5.0 Architecture	DDT&E	To First Mission	Through Third Mission
Case 1a: ECLSS O_2 and N_2/Ar with Earth H_2 – Solar Powered	86%	88%	90%
Case 1b: ECLSS O_2 and N_2/Ar with Earth H_2 – Nuclear Powered	100%	100%	100%
Case 2a: ECLSS O_2 and N_2/Ar with Mars H_2O – Solar Powered	140%	146%	152%
Case 2b: ECLSS O_2 and N_2/Ar with Mars H_2O – Nuclear Powered	131%	132%	134%
Case 3: ECLSS and Propellant O_2 and N_2/Ar with Earth H_2 and CH_4 – Nuclear Powered	103%	104%	106%
Case 4: ECLSS and Propellant O_2 and N_2/Ar with Mars H_2O – Nuclear Powered	191%	202%	213%

- Requirements Analysis
  - Morphological matrix put into SysML, automatic filtering
  - Automatic model generation & sizing from qualitative selections

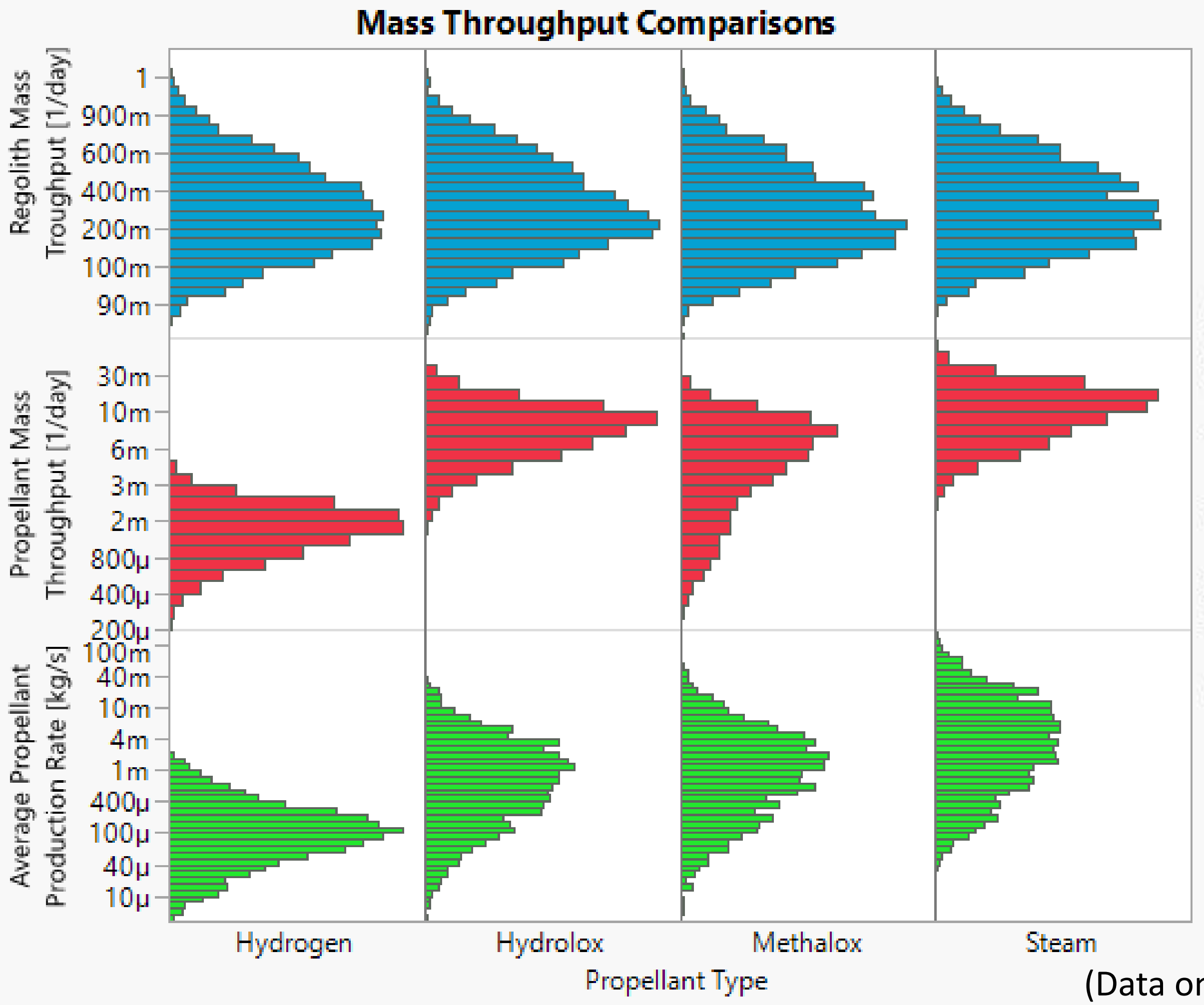


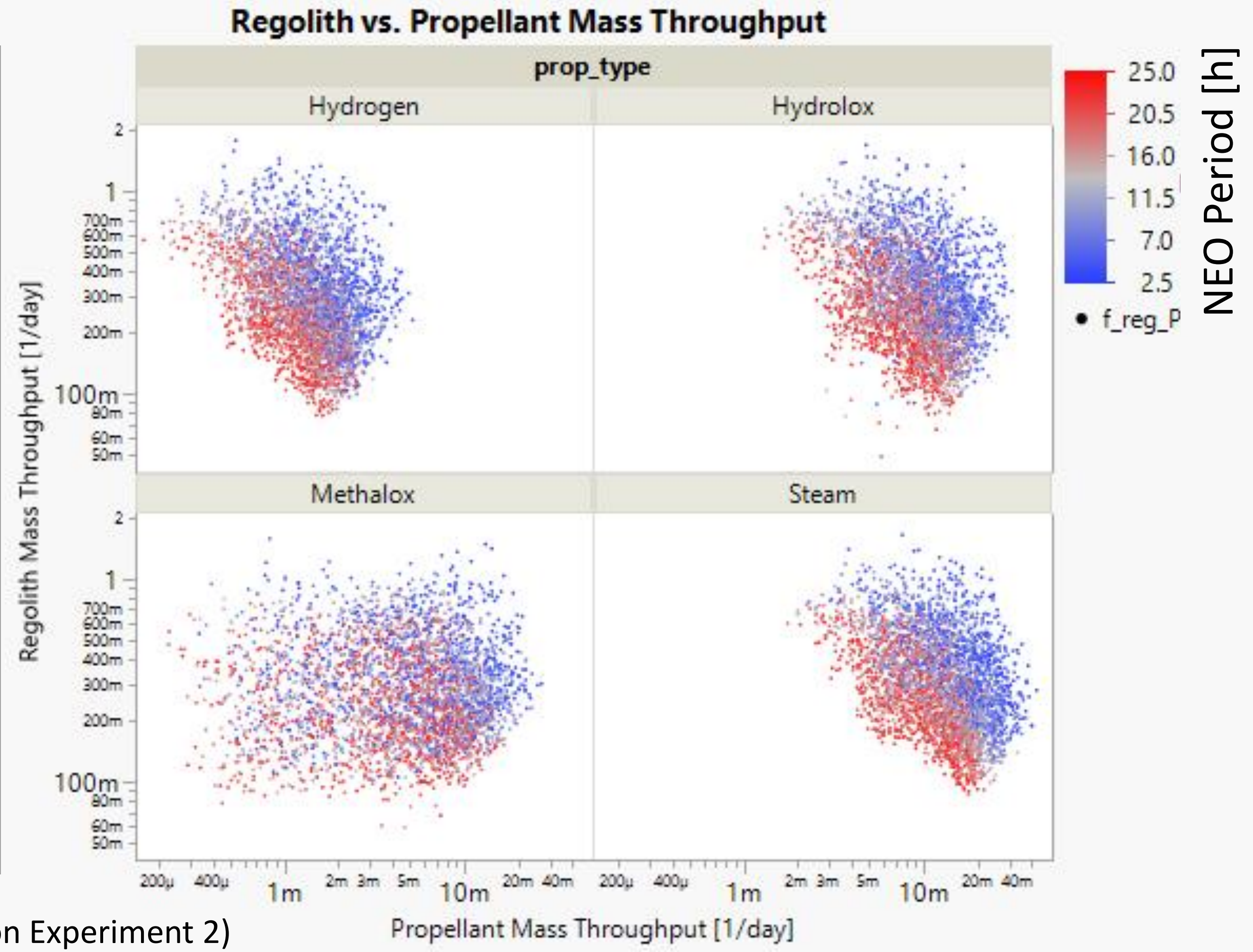
- Space Logistics Code Integration

Questions?

kitsonc (at) gatech.edu

Mass Throughput Distributions

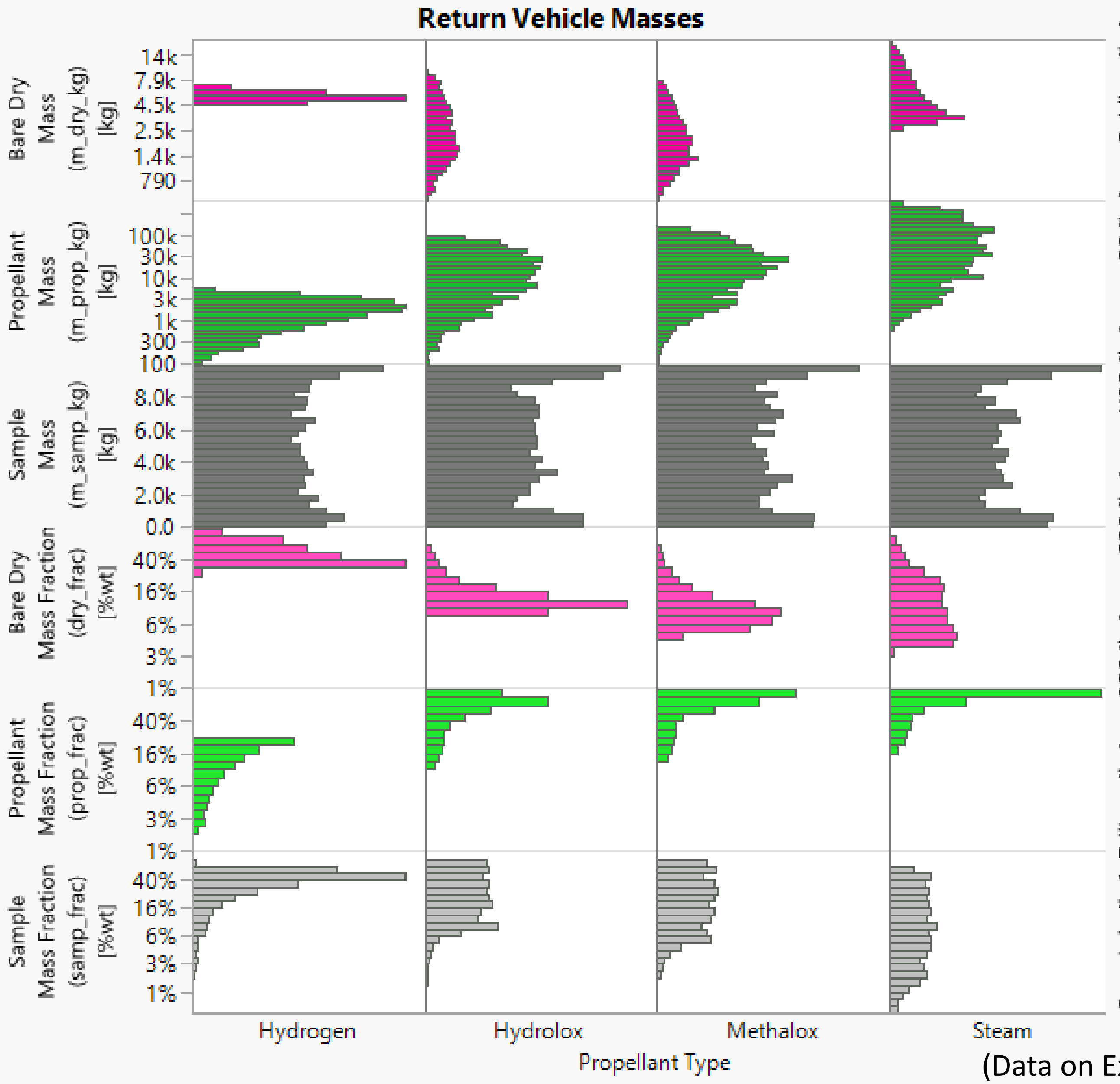


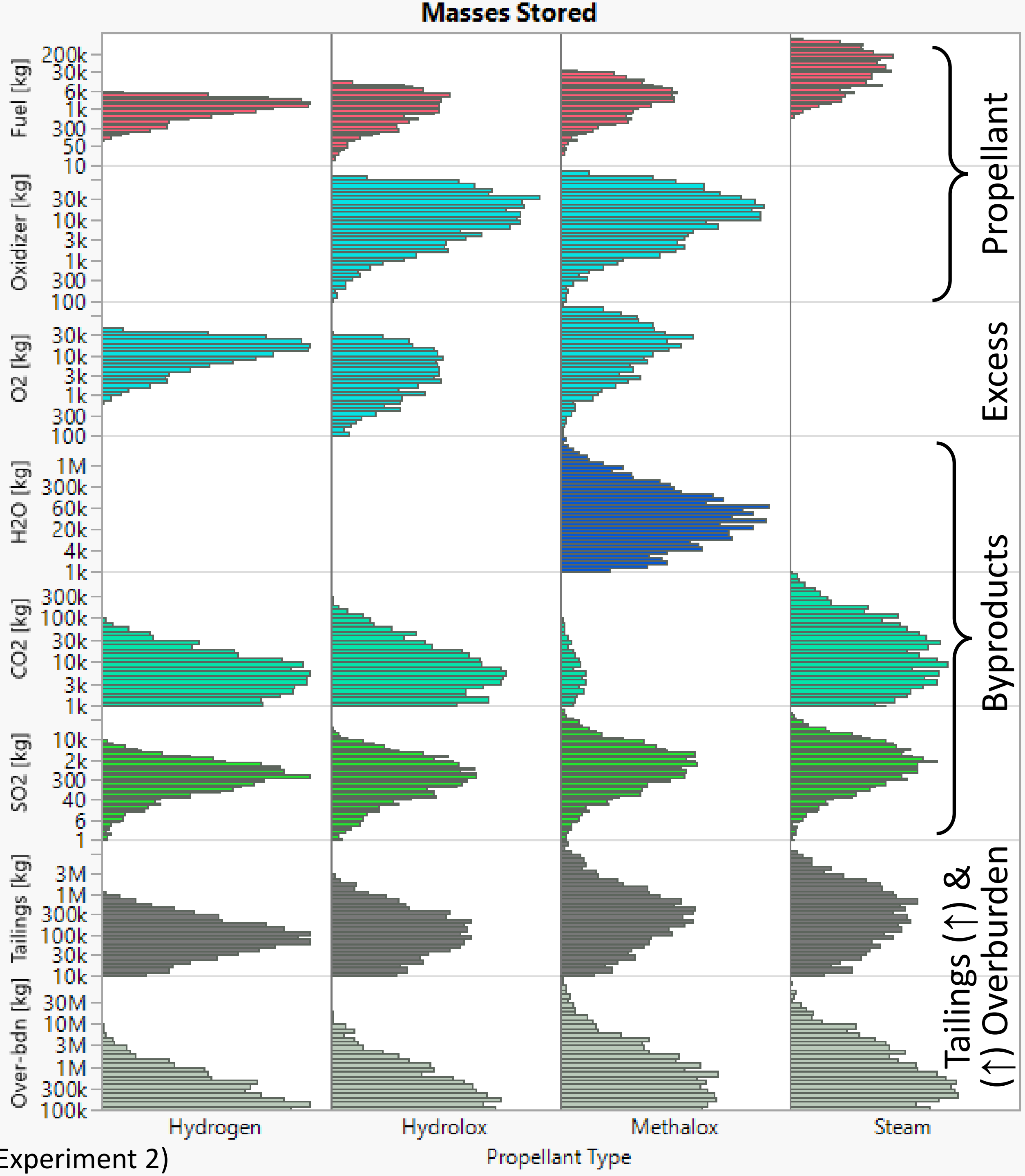


(Data on Experiment 2)

Mechanism for relationship unknown

Mass Distributions





(Data on Experiment 2)

Identified Systems within an ISRU SoS

Direct

Critical path elements in processing

- Prospecting
  – find the ore in the NEO
- Excavation
  – separate the ore from the NEO
- Extraction
  – remove the resource from the ore
- Refining
  – process & purify into a consumable
- Storage
  – maintain stocks with minimal loss
- Material Handling / Transport
  – move masses between equipment

Indirect

Support other systems involved in ISRU

- Avionics
  – command and communications to coordinate SoS
- Power Management
  – provide sufficient energy for NEO operations
- Thermal Management
  – dissipate excess thermal energy to prevent overheating, and provide sufficient heat
- Wastes
  – end states for processed matter besides products
- Structures
  – bear mechanical loads, control attachment to NEO

Prospecting

Prospecting is the discernment of locations with greater concentrations of space resources on or within the target NEO that are reasonably accessible.

- **Local Observations** refers to the primary method of gathering information in the vicinity of the body of interest without direct contact.
- **Wave Type** describes oscillations in a medium that are used to gather data.
- **Sampling** refers to methods of disturbing NEO regolith to ascertain its properties.

Excavation

Excavation is the process of separating the ore from the NEO, or otherwise directly interacting with the NEO to release resources.

- **Containment** is isolating a volume to prevent material from floating off, preferably also involving a gas-tight seal.
- **Cut Rock** refers to methods to separate material from the NEO.
- **Powderize** or comminution refers to means for a reduction in particle size of the excavated rock, if desired.
- **Sorting/Sizing** is means of differentiating between excavated substances, especially by size.

Extraction

Extraction refers to the removal and purification resources of interest from their ores.

- **Primary Heating** refers to methods to raise the temperature of the material being processed, especially for the sublimation of volatiles like water.
- **Beneficiation** refers to methods to concentrate or increase the grade of a resource, by separating out other parts not of interest.
- **Volatile Capture** describes methods to isolate the resource(s) extracted from the ore, for further refinement or storage.

Refining

Refining is defined here as the processing of resources from an intermediate state into a readily useable form termed a consumable. These categories focus on propellant production.

- **Make Oxygen** refers to methods to obtain elemental oxygen from NEO resources.
- **Make Hydrogen** refers to methods to obtain hydrogen gas from NEO resources.
- **Crack Hydrocarbons** refers to methods to decompose organic molecules.
- **Make Methane** or methanation, refers to methods to synthesize simple hydrocarbons from other chemical species.
- **Quality Control** refers to methods to verify that the propellant produced is of sufficiently high purity (meeting a standard) to be used by the return vehicle.

Storage & Wastes

Storage refers to methods for preservation of consumables for future use.

- **Medium** refers to the form of matter that the consumable is in during storage, along with a closely related confinement method
- **Insulation** refers to passive methods to maintain the consumable within a preferred temperature range for storage.

Waste management refers to the end state of matter processed within the ISRU SoS that is not part of the desired quantity of consumables (e.g. propellant).

- **Tailings & Overburden** comprise the unwanted granular solids produced.
- **Byproducts & Excess** comprise the unwanted fluids produced.

Material Handling

Introduction
Motivation
Methodology
Implementation
Conclusions

Material Handling examines methods to transport mass between locations.

- **Fluids** conveyance for liquids and/or gasses, which are notable for their ability to flow and defined by their properties under shear.
- **Granular Solids** conveyance for discrete solid particles or powders which have properties in betwixt solids and liquids .
- **Work Input** is the primary method of providing energy for material handling.

Avionics

Avionics or data system refers to the command, control, and communication aspects of coordinating a SoS.

- **Autonomy** refers to the locus of decision making within the SoS and the methods to troubleshoot control logic to ensure tasks are carried out according to plan.
- **Computation** refers to implemented instruction set architecture, or how computer processing nodes are distributed within the SoS.
- **Local Comms** refers to how instructions are sent between systems within the SoS.
- **Deep Space Comms** refers to the means of long range communications between spacecraft(s) in 'deep space' and responsible personnel back on Earth.

Power

Power management refers to the primary means by which electrical energy is harnessed throughout the SoS.

- **Electrical Generation** is the primary means by which sufficient electricity for all operations on the NEO is provided, when and where it is needed.
- **Energy Storage** refers to methods to store charge and/or smooth power demand.

Thermal

Thermal management refers to active methods by which the thermal energy of systems within the SoS is kept within permissible limits.

- **Secondary Heating** is defined here as a supplemental method to add additional thermal energy into the SoS, where the extraction heating subsystem is the primary.
- **Cooling** is the dissipation of excess thermal energy to prevent overheating.
- **Heat Exchangers** aid thermal energy transferring into, out of, and between fluids.
- **Distribution** refers to methods to transfer thermal energy from one location to another within the SoS, especially though the use of coolant loops.
- **Beam Transmission** refers to methods to transfer electromagnetic waves throughout the SoS, especially for cutting or heating with focused light.

Structures

Structures refers to equipment designed to bear mechanical loads and maintain control of the spacecraft.

- **Support Structure** refers to the backbone to which other modules are secured to, and is the primary means of conveying structural loads within the spacecraft.
- **Positioning** refers to ways to counteract reaction forces to maintain contact with another body; stay at a given location.
- **Relative Motion** refers to methods to reposition systems with respect to another body; change locations deliberately.
- **Rotation Control**, or de-spin and de-wobble, refers to methods to slow the rate of rotation about its axis or arrest secondary tumbling motions.