A SYSTEMS OF SYSTEMS METHODOLOGY FOR CONCEPTUAL STUDIES OF IN-SITU RESOURCE UTILIZATION FOR NEAR EARTH OBJECT APPLICATIONS

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A SYSTEMS OF SYSTEMS METHODOLOGY FOR CONCEPTUAL STUDIES OF IN-SITU RESOURCE UTILIZATION FOR NEAR EARTH OBJECT APPLICATIONS

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Lastly, thanks be to you, the reader, for your time and attention. Without you, this work would be gathering proverbial dust on a server somewhere, forgotten. This thesis may not be the most succinct, but hopefully it is clear and a thorough foundation to build upon, onwards and upwards to the stars. *Ad Astra!*

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LIST OF ABBREVIATIONS

Shorthand for ideas of note within this work are listed here for reference. Note that abbreviations from appendices are generally specified in place, instead of inclusion herein. Abbreviations are generally specified the first time they are used in each chapter. Special abbreviations for research questions and their resolution are included first for reference.

Q#	Research Question #; a notable line of examination for this thesis
P#	Research Plan #; steps to be taken to resolve research question #
H#	Hypothesis #; the proposed answer to research question #
E#	Experiment #; constructed to evaluate the validity of hypothesis #
R#	Result #; conclusions on hypothesis #, resulting from original research
C#	Conjecture #; a response to research question # from available info

ARM	NASA Asteroid Retrieval Mission; also Asteroid Redirect Mission
ASME BPVC	American Soc. of Mechanical Engineers Boiler & Pressure Vessel Code
CAVoR	Pioneer Astronautics' Carbonaceous Volatile Asteroid Recovery system
CBS	Capability Breakdown Structure
CDRA	ISS Carbon Dioxide Removal Assembly; also CO_2 Reduction Assembly
COTS	Commercial Off-The-Shelf; developed design available for purchase
C-type	Carboneaceous chondrite asteroid with spectral classification within Tholen C-type or largely equivalent Bus-DeMeo C-class
DoE	Design of Experiments
DRA 5.0	NASA Human Exploration of Mars Design Reference Architecture 5.0

ESA	European Space Administration
GAO	U.S. Government Accountability Office
HabNet	MIT Strategic Engineering Research Group’s integrated habitation and supportability architecting and analysis environment
Hydrolox	Hydrogen-oxygen bipropellant
ISPP	In-Situ Propellant Production
ISRU	In-Situ Resource Utilizaion
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit
Methalox	Methane-oxygen bipropellant
MIT	Massachucets Institute of Technology
NASA	U.S. National Aeronautics and Space Administration
n.d.	non-dimensional or unitless parameter
NEA	Near Earth Asteroid
NEO	Near Earth Object
OSIRIS-REx	NASA’s Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer, sample return mission to C-type Bennu
PDF	Probability Distribution Function
PEM	Proton Exchange Membrane electrolyzer, also Polymer Electrolyte Membrane electrolyzer
PVEx	HoneyBee Robotics’ Planetary Volatiles Extractor
SNIPT	Sample return from Near earth object (NEO) with In-situ Propellant production (ISPP) Technology demonstrator
SoS	Systems of Systems
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level

LIST OF SYMBOLS

Definitions of symbols by the natural quantities and units they represent are provided.

a	$[\mathrm{m/s^2}]$	Acceleration – in meters per second squared
A	$[\mathrm{m^2}]$	Area – in square meters
C	[%wt]	Concentration of a Chemical Species – in weight percent
$CONT$	$[\%wt]$	Mass contingency factor for system sizing – weight percent
D	[AU]	Heliocentric distance – in astronautical units
f	$[1/\mathrm{day}]$	Mass throughput ratio – kg processed per kg equipment day
(script L) ℓ	[m]	Length – in meters
I_{SP}	[s]	Specific Impulse – in seconds
m	[kg]	Mass – in kilograms
$\dot{m}$	$[\mathrm{kg/s}]$	Mass Flow – in kilograms per second
MPR	$[\mathrm{n.d.}]$	Mass payback ratio – kg produced per kg equipment
(eta) η	[%]	Efficientcy – in percent, non-dimensional
n	[mol]	Number of Moles of a Chemical Species – in moles
N	[#]	Quantity / Number – integer, normally rounded up
(rho) ρ	$[\mathrm{kg/m^3}]$	Density – in killograms per cubic meter
p	$[Pa]$	Pressure – in pascals
P	[We]	Electric power load – in watts electric
PMP	$[\mathrm{kg/kW}]$	Power mass penalty – in kilograms per kilowatt
Q_C	[Wt]	Cooling load – in watts thermal

Q_H	[Wt]	Heating load – in watts thermal
r	[m]	Radius – in meters
§	N/A	Section, of current document
SEI	[J/kg]	Specific Energy Intensity of propellant – in joules per kg
(tau) τ	[m]	Thickness – in meters
t	[s]	Time – in seconds, or months
T	[K]	Temperature – in Kelvin
$UseReg$	[%wt]	Useful proportion of regolith – in weight percent
$UseVols$	[%wt]	Useful proportion of evolved volatiles – in weigth percent
v	[m/s]	Velocity – in meters per second
Δv	[km/s]	Change in Velocity ('delta vee') – in kilometers per second
(xi) ξ	[%en]	Energy use fraction – in percent energy of aggregate total
(zeta) ζ	[%wt]	Mass fraction – in percent weight of aggregate total

SUMMARY

Near Earth Objects (NEO) have historically been neglected as an object of study relative to other celestial bodies. Interest has been increasing as more recognize the potential value of NEO resources represented by ‘asteroid mining’, especially as a supporting role in a Systems of Systems (SoS) context. After all, reusable rockets require refueling before reuse. That propellant needs to come from somewhere.

Still, a feasible means to harness NEO resources has proven elusive. In-Situ Resource Utilization (ISRU) is a broad field with literature siloed by both disciplines and use cases. This is especially apparent for existing NEO ISRU concepts, with wildly varying levels of detail between systems in the same concept, including omission of key functions. Pet projects given context imply ‘technology push’ instead of ‘mission pull’.

This thesis aims to show NEO ISRU is more feasible than previously believed, by providing a more comprehensive treatment of the required functionality and the means to deliver it. This boils down to permitting better comparisons via enabling trade studies at the conceptual level (NASA pre-phase A). A sample return mission using propellant produced from NEO resources for the return trip is formulated to contextualize the analysis. A program to develop a design that accomplishes this mission could be named “Sample return from Near earth object with In-situ Propellant production Technology demonstrator” (SNIPT). Both qualitative and quantitative design aspects are considered herein.

Qualitative aspects are considered first. By reconciling commonalities between concepts, standardized terminology is proposed through a functional decomposition along with a morphological matrix of alternatives. A streamlined technology readiness assessment is performed to rank these morphological options. This information is used to select four concepts, one for each propellant type considered. Both impulsive (methalox and hydrolox) and continuous (hydrogen and steam) propulsion are considered as possible customers of an In-Situ Propellant Production (ISPP) SoS.

Another significant part of this effort is quantifying alternatives sufficiently to permit comparisons beyond subject matter expert opinions. A modular sizing code is developed from scratch in line with the selected morphological options for each propellant, and verified at the module level using analog test data. By establishing baseline design(s), perturbations can be compared with directionally correct results. Input parameters for NEO orbital characteristics and then NEO composition are varied to ascertain effects upon sizing results. These results inform a trade study between the four propellant types considered.

It was found that previous modeling efforts for NEO ISRU concepts have grossly underestimated the overall plant mass, likely due to neglecting indirect ISRU functionality and energy use. This includes sized values for mass payback ratio (MPR ≈ 5) and mass-specific regolith throughput ($f_{REG} \approx 0.3 \text{ day}^{-1}$) which were previously overestimated by orders of magnitude. Methalox works better above 5 C: 1 H atoms by mass, a restrictive niche. Steam had the highest MPR but also heaviest plant mass. Hydrolox was found to be lightest on average for low Δv, with hydrogen lighter for high values, though hydrogen had MPR < 1 due to low volatile utilization. Increasing the proportion of volatiles used to make the propellant was found to reduce specific energy intensity, which in turn increases MPR.

CHAPTER 1. INTRODUCTION

In-Situ Resource Utilization (ISRU) is a broad ranging set of capabilities with great promise, but one that has had trouble getting off the drawing board. The ability to 'live off the land' to varying degrees in space harks both a fundamental paradigm shift in what is possible, as well as the difficulty of stakeholder buy-in [1], [2]. The more ingrained ISRU is into a design the more benefits accrue, though this dependency also imbues systematic risk and long development timelines given current technology [3]. The schedule and risk disbenefits are often deemed too much for flight missions time and time again, sending ISRU back to the drawing board in a 'chicken or the egg' cycle.

It is also worth noting that this cycle is due in part to ISRU most commonly being proposed as a part of crewed exploration campaigns [4]. Associated missions tend to have the most massive payloads considered, with the promise of reduced cumulative payload mass over time posed by ISRU giving the greatest benefit here. However, the presence of crew also imposes more stringent safety protocols and lower risk tolerance than other space missions. Having an unproven set of technologies being on the critical path to success, like providing ascent propellant to return, is usually a step too far for program managers [3].

If ISRU is to be adopted in the future, it must first be proven in an environment with a lower consequence of failure [5]. Analog testing of prototypes on Earth has attempted to fill this niche, but more testing in relevant or operational environments is still perceived as needed for stakeholder buy-in [4], [6], [7]. The Artemis Program appears to address these concerns by gradually increasing ISRU involvement in non-critical aspects of follow-on missions, as seen in Figure 2-9 [8]. Another option is to conduct a technology demonstration mission to a Near Earth Object (NEO), with an eye towards technology transfer. Rendevous with NEO can be construed as less difficult than landing on other celestial bodies, and NEO resources can be used to support a larger campaign.

1.1 Focus of Research

Still, there is much skepticism as to the merit of such proposals, and the feasibility of and/or risk involved in any ISRU concept. This prejudice is especially true for NEO ISRU. 'Asteroid mining' is not typically seen as a serious proposal by many scholars, in large part due to concerns about cost, risk, technology, and gaps in the concept of operations. Given the cursory piecemeal treatment of the topic by the prior art in the literature, these concerns do have merit.

This thesis aims to show NEO ISRU is more feasible than previously believed, by providing a more comprehensive examination of the required functionality and the means to deliver it. A significant part of this effort is the synthesis of siloed efforts with differing emphasis. By reconciling commonalities between concepts, steps can be taken towards establishing standardized terminology. Another significant part of this effort is quantifying the performance of alternatives sufficiently to permit comparisons beyond subject matter expert opinions. By establishing baseline design(s) and a sizing framework, perturbations can be compared with directionally correct results. Taken together, these two thrusts aim to enable more rigorous trade studies between NEO ISRU concepts at the conceptual level.

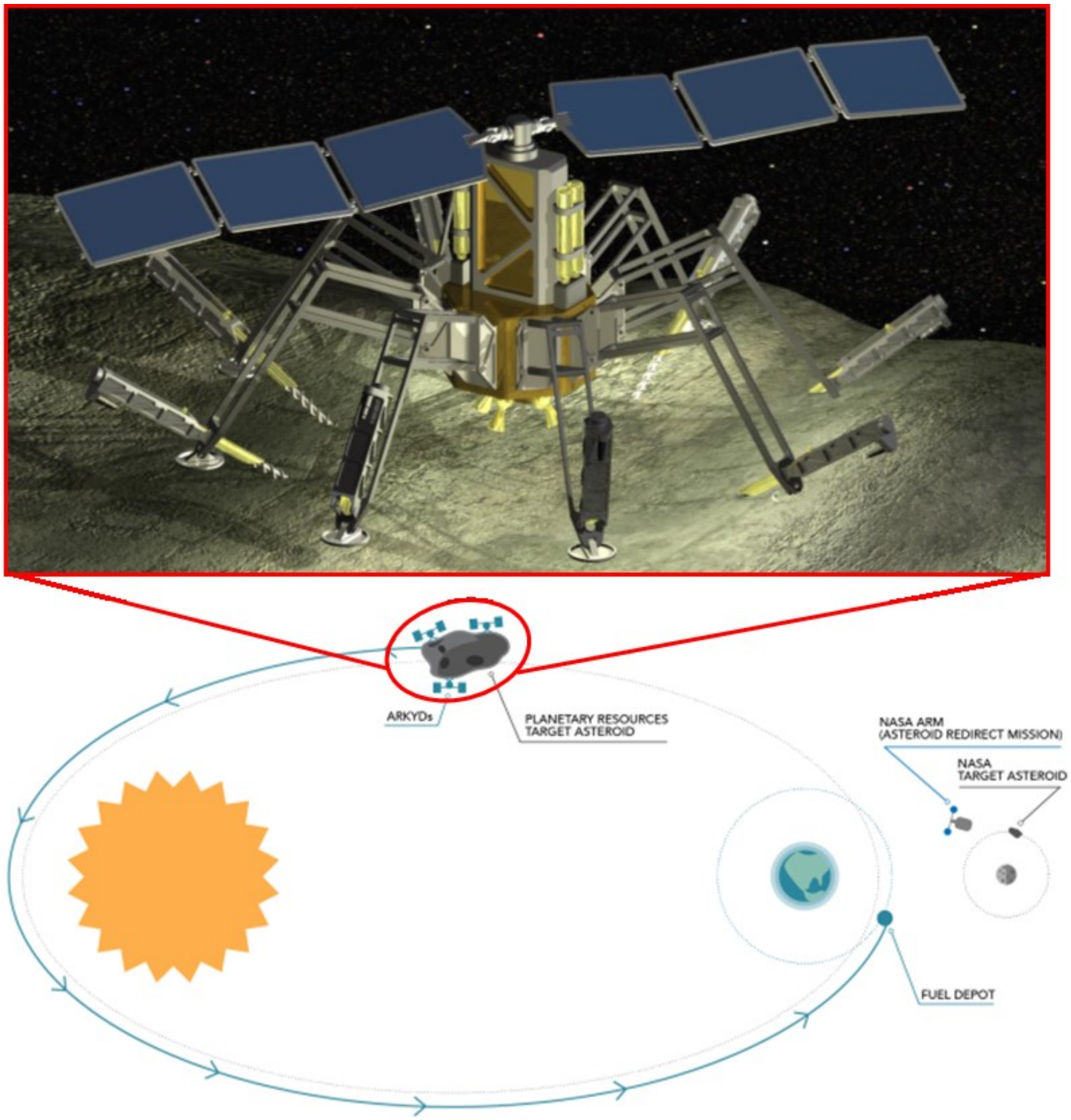


Figure 1-1: The focus of research, visualized (HoneyBee Robotics' Spider top [9], with Planetary Resources visualization below [10])

A method will be created to address these concerns, and to be generally applicable beyond the scope of this work. In this spirit, the ideas discussed here will be generalized through the use of less technical language. The use of space resources (ISRU) shall be generalized to 'industrial activity in outer space', with the focus on operations in the vicinity of NEO such as asteroids. The desire for trade studies and standardized terminology shall be generalized to a desire 'to better compare concepts'. Thus, the focus of research was arrived at, and visualized in Figure 1-1. This figure shows a notional NEO ISRU concept in focus, noting that its operations occur within a larger context. Note that the focus of research is developed into the more technical research objective, as more concepts are introduced throughout the next chapter.

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

Since this focus is quite broad, a more specific treatment is used throughout the rest of the thesis to make headway. In this vein a mission is selected for analysis, with two case studies performed to quantify the differences between design concepts. This mission is simply stated below, with further detail unfolding as the thesis develops.

Selected Mission (simplified)
Examine a pilot plant deployed to an asteroid, which is designed to produce enough propellant to return a given mass to Earth orbit.

Sections discussing the rationale for and details of the selected mission:

§ 2.4 – Contrasting Destinations
§ 3.5 – Mission Selection
§ 4.2 – Functional Decomposition
§ 5.1 – Capturing Inputs for Modeling
§ 7.2.3 – Design Recommendations for NEO ISRU Concepts

1.2 Structure of this Work

Before jumping in further, an explanation on the structure of this thesis is in order. Each chapter delves into a key aspect of this work, and is backed up by an appendix where additional detail is felt to be merited.

Chapter 1 – Introduction provides a brief overview of this work.

Chapter 2 – Motivation contextualizes this thesis by introducing relevant concepts and relating them. ISRU infrastructure is shown to be a key enabler, yet major gaps exist in both modeling and perspective in previous development efforts. This chapter ends with the Research Objective, which is a more technical version of the Focus of Research.

Chapter 3 – Methodology introduces a process to examine how both the qualitative and quantitative aspects of conceptual comparisons can be addressed. The selected mission and case studies used for this research are also examined here.

Chapter 4 – Qualitative Design Aspects: Morphology of the Design Space contextualizes and preforms qualitative comparisons of concepts. A functional decomposition is performed to capture required functions. A literature review is conducted to identify corresponding morphological options, with existing NEO ISRU concepts treated individually in Appendix A – Review of Existing Concepts. A streamlined technological readiness assessment is then preformed to rank identified morphological options, with definitions and reasoning documented in Appendix B – Technology Readiness Level Assessment of Morphological Options. This information is then used to select four concepts, one for each propellant type considered (steam, hydrogen, hydrolox, and methalox).

Chapter 5 – Quantitative Design Aspects: Conceptual Sizing expands upon the selected concepts by describing how they can be quantified. Important input parameters are considered, and default values found in the literature. A modular sizing code is introduced at a high level, with more detail in Appendix C – Sizing Code Relations. Output metrics to compare concepts are then introduced. The chapter wraps up with a high level overview of code module verification efforts using analog test data.

Chapter 6 – Case Studies details the two experiments conducted to compare the three selected concepts, as they are sized for varied input values. Experiment 1: NEO

Orbital Characteristics primarily examines how varying mission parameters and solar radiation effects affect the sized mass of each concept. Experiment 2: NEO Composition examines how varying volatile composition in addition to orbital characteristics affects the sizing result.

Chapter 7 – Conclusions wraps up the work by reflecting with observations. The results of the trade study between the four propellants is discussed. Takeaways from this work are discussed, and the research questions resolved. The thesis finishes with several topics of recommended future work to build upon this one.

These topics will be introduced and discussed periodically throughout the thesis. Many arise from applying techniques from other related fields to ISRU, while others are distinct in their own right. Before arriving at such a juncture though, this work must be motivated and further unfold to provide context on these contributions.

CHAPTER 2. MOTIVATION

Three questions the reader may be asking themselves are as follows:

- 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?

This chapter aims to answer these questions, and thereby explain the raison d'être for work.

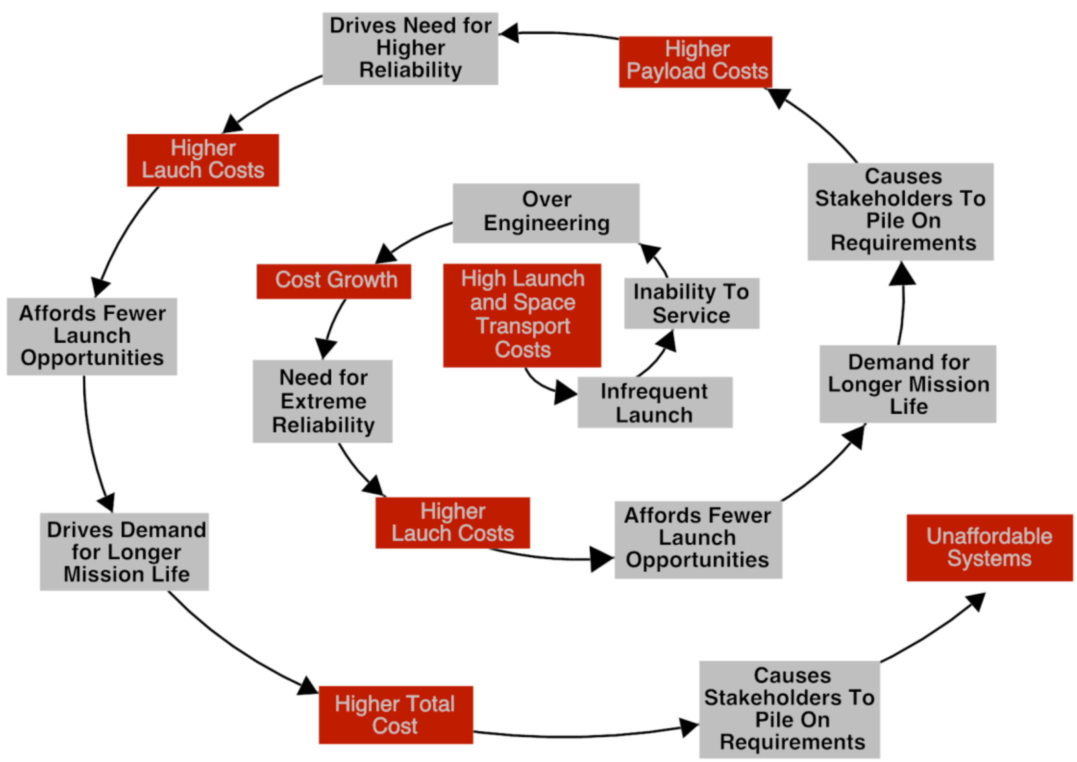


Figure 2-1: Spiraling space mission costs [11]

To start, current practices for space missions are not sustainable. A spiral of increasing costs exists in the design process (see Figure 2-1), that has effectively constrained the scope of both government missions and commercial activity in space [11].

Higher costs ultimately mean fewer missions, and less science for national space agencies. Higher costs also mean fewer missions from commercial partners, and less investment from fewer perceived opportunities for growth.

Thus, a paradigm shift is needed to achieve low cost access to space, and perhaps someday 'to boldly go' where no one has gone before [12]. In this vein, the commercialization of space can be understood as an effort to decrease costs for participants, and increase opportunities for non-governmental actors to become involved [13], [14]. If 'we are going' and do not have unlimited funding, then new approaches and thinking are necessary to go in "a manner that is wholly different than 50 years ago" [15].

2.1 Background Concepts

Since man first set foot on the moon a little over fifty years ago, the space community has yearned to do more. This yearning manifests in two important debates: were to go, and who will pay for it. Since the business case currently does not close for private space exploration, this domain has become a scientific endeavor supported by the government and subject to political whims [16]. The most recognizable debate in this area has been whether to aspire to send humans first to the Earth's Moon (henceforth Luna) or Mars. The scientific community has developed plots like Figure 2-2 below to visualize high level requirements such as round-trip duration and propulsive energy (Δv) to compare these missions [17]. Note that here, the round-trip Δv includes everything from launching from Earth, escape velocity from Low Earth Orbit (LEO), deceleration at the destination, landing, then launching again, boosting back to LEO, and finally splashdown back on Earth's Surface.

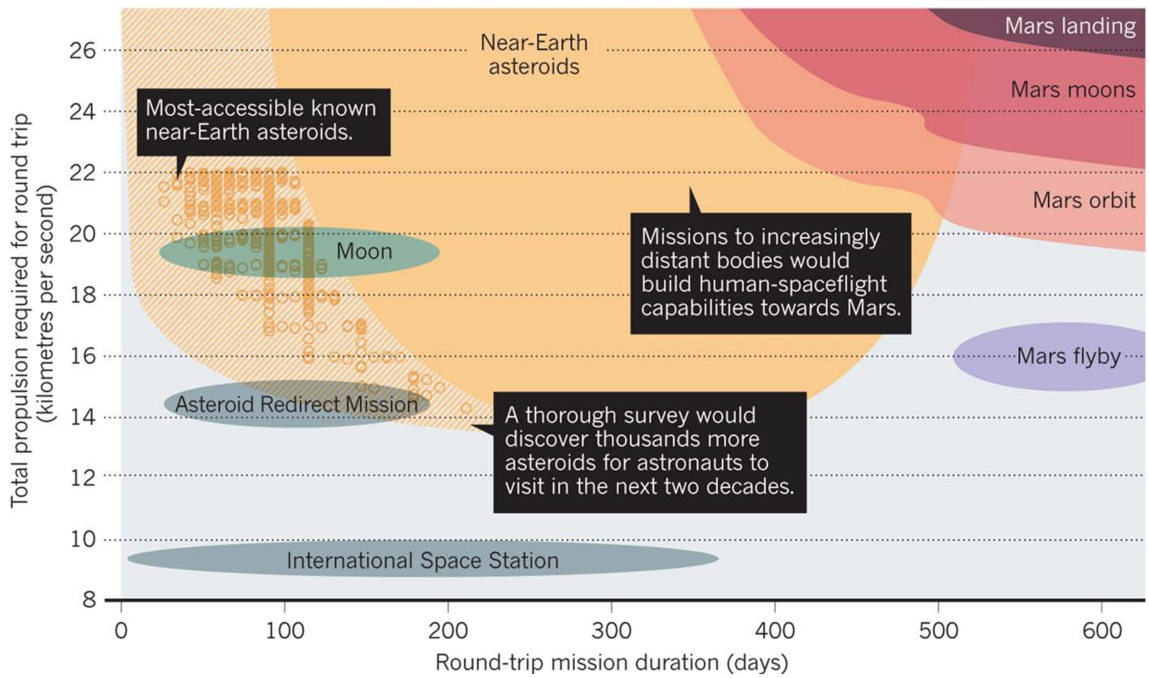


Figure 2-2: Human spaceflight destinations [17]

2.1.1 Near Earth Objects

However, this Luna versus Mars debate is more of a false dichotomy. There is a whole additional class of relatively smaller objects within this region of space that is generally overlooked, termed Near Earth Objects (NEO) [18]. The term NEO is preferred over asteroids (NEA) in this thesis, because it is more inclusive on composition to also include comets, yet restricts the options to those whose orbits are more accessible from Earth. This is not a new idea, as epitomized by the Keck Institute Asteroid Retrieval Feasibility Study, which evolved into NASA's (canceled) Asteroid Retrieval Mission [18], [19]. It is these NEO that offer the alternative destinations shown in Figure 2-2 that are less demanding than a mission to Mars, and some that are even less demanding than a mission to Luna [16]. NEO have two major advantages over planets and their moons: it is far easier to leave their surface, and there are far more destinations to choose from [20].

Studies of NEO have been historically motivated by planetary protection efforts, and NEO have usually been viewed in terms of impact risk, as in Figure 2-3 [21]. This is done to ensure sufficient warning is given for objects that travel too close to Earth and enter its atmosphere, which are then termed meteors. All NEO loose mass through ablation while traveling through the Earth's atmosphere, and most breakup in 'airbursts' before impacting the Earth's surface. Fragments of NEO that strike Earth's surface are termed meteorites.

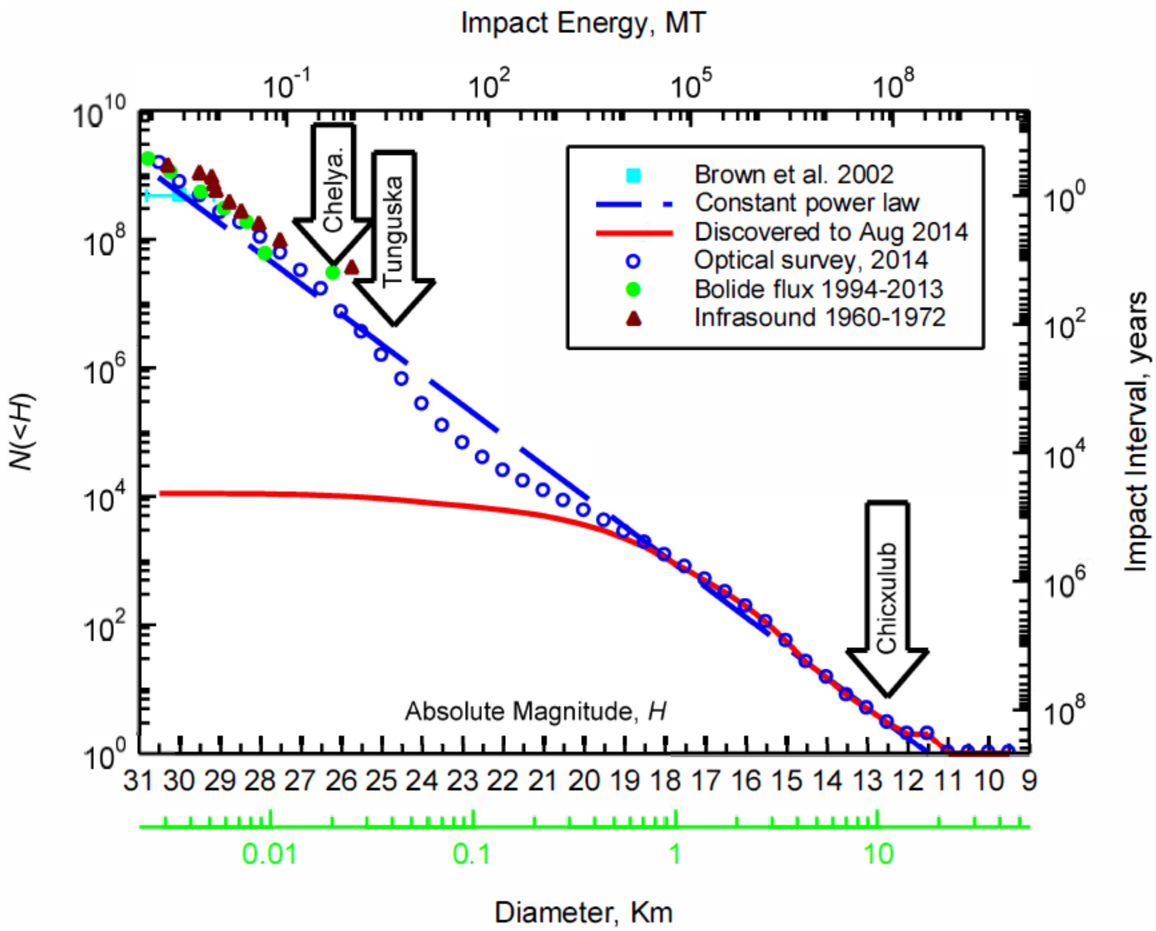


Figure 2-3: Estimated cumulative population of Near Earth Asteroids by size [21]

Still, just because NEO are 'relatively small' for celestial bodies does not mean they are small in absolute terms, with sizes ranging from meters to kilometers across [21]. Large asteroid impacts are a notable cause of mass extinction events, such as that of Chicxulub roughly 66 million years ago which is thought to have felled the mighty dinosaurs [22]. Though only a slim few NEO can cause extinction level events, most can deal serious damage. The 1908 Tunguska meteor was estimated to be a 3-5 megaton TNT airburst which flattened 825 square miles of forest in Siberia, while the 2013 Chelyabinsk meteor was estimated to be a 500 kiloton TNT airburst [21], [23]. These notable historical impacts are put in context of impact severity, and the estimated cumulative NEA population (without comets) in Figure 2-3.

Though this data on the cumulative population of NEO has been largely derived from planetary protection surveys, it is also important to note the high degree of aleatory uncertainty in the data. More specifically, the quantity of NEO discovered to date is orders of magnitude below the quantity of NEO estimated to be in this region of space [21]. Case in point, the 2013 Chelyabinsk meteor was not identified until after it entered the Earth's atmosphere, and the best guess at the time was later determined to have the wrong type of composition [23]. The dearth of knowledge about small NEO is especially acute in Figure 2-3, as the red line of discoveries lies far below all models of the NEA population shown. Note that this is a logarithmic scaled plot, with the number of NEA counted cumulatively from the right to the left on the axis to the left. Since the line has negligible slope for smaller diameter NEA, this means that very few have been identified. Figure 2-2 also notes this fact, by extending the Pareto frontier of possible NEA destinations at the edge of the tan region to shorter and less energetic missions than those represented by the points of known NEA shown on the plot. Thus when considering NEO as a destination, it is prudent to parameterize their characteristics because it is probable a more ideal destination will be discovered before the mission is conducted.

2.1.2 Space Logistics Context

Of course NEO may not be the primary destination for the mission, but rather a waypoint along the way. Additional stops add complexity and time to the mission, but can lend themselves to lower mass vehicles with larger deployed payloads. These sorts of problems are typically examined within a space logistics framework. By monitoring resource consumption along the way, resupply options and architectures with many interacting systems can be studied. These frameworks tend to use time expanded networks of nodes, to preform trade studies upon the number of vehicles, their routes, and their cargo [24], [25]. NEO fit into these space logistics studies by being a potential source of resources to be used elsewhere. Popularly termed 'asteroid mining', this act can be more broadly categorized as a form of In-Situ Resource Utilization (ISRU) [20]. Efforts have been made to integrate NEO ISRU into campaign level models to Luna and Mars [26].

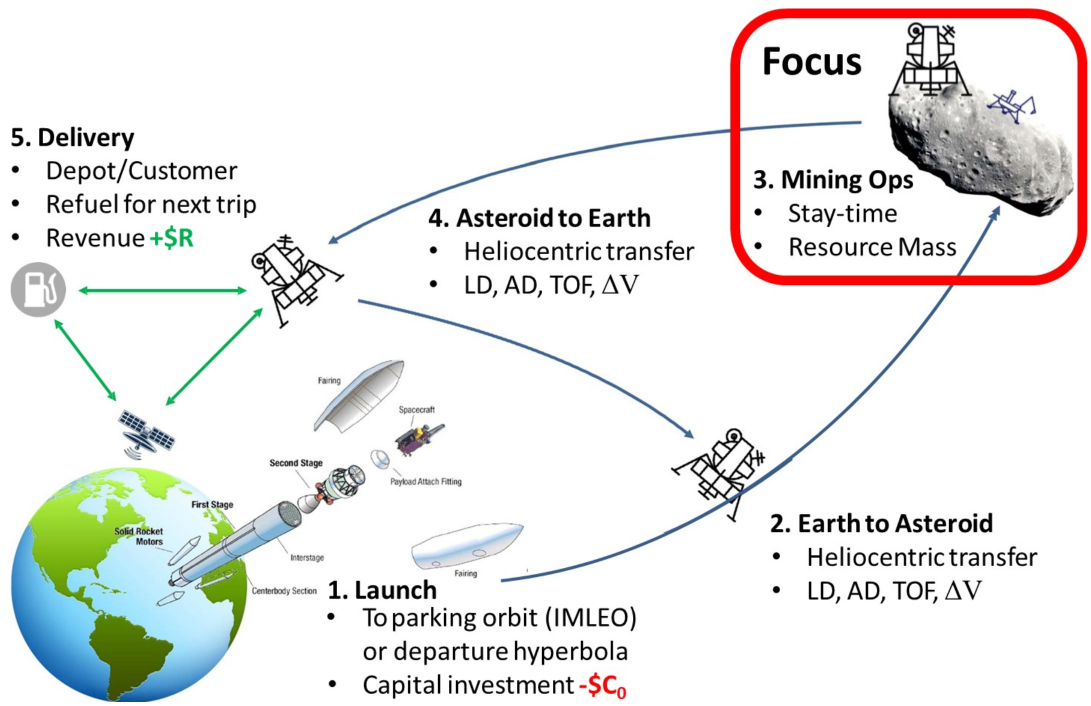


Figure 2-4: Asteroid Mining in the Context of a Space Logistics Framework (adapted from [27])

A simple mission to a NEO with a single departure and return trip that could be modeled in such a framework is shown in Figure 2-4 [27]. This mission attempts to describe the 'minimum viable product' for a hypothetical asteroid mining operation, and different high-level design variables associated with such a mission. The space logistics community has studied many variations on this problem, focusing primarily on the routing of resources, and how NEO resources might be used supply chain network [28]. Typically the resource is water, and the application is providing propellant.

2.1.3 In-Situ Resource Utilization

Though propellant production is one form of ISRU, it is far from the only one. ISRU is a family of techniques that includes any form of producing something of value from local materials, while not on the Earth's surface [29]. Resources can be nearby rocks, waste, or even ambient conditions [7]. Due to the breadth of activities included, ISRU encompasses most types of industrial activity in space (see Figure 2-5). This includes producing consumables like oxygen, as well as spare parts or structures [20]. Notably, the discovery of Lunar water ice plays a large role in the motivation for the Artemis Program, and the possibility for a sustainable presence there [8].

The primary benefit to utilizing local resources is a reduction in mass launched from Earth, though this must be balanced with the mass, time, and complexity of the processing equipment to be used [30]. Risk is also an issue, as making supplies required for the mission during the mission itself puts more actions on the critical path, not to mention introducing additional failure modes or unproven technologies [3]. These impacts must be carefully considered for design concepts including ISRU.

Figure 2-5: Types of IRSU [29]

2.1.4 Systems of Systems Engineering

For the purposes of this thesis, a 'design' is a set of specifications for how to accomplish a goal. That goal can be a function, purpose, task, or mission. A 'mission' is often the design goal in aerospace engineering, where a series of states are achieved and/or actions done in a specified order. Similarly, these specifications are a list of choices that were made that differentiate a particular design from other similar designs. Depending on the level of detail included, this design can be a vague concept or detailed product specification. Depending on the goal, the design can exist at several design levels such as a subsystem, system, or system of systems (SoS). These ideas can be related through a hierarchy of subsets and supersets, as shown in Figure 2-6 [31].

Subsystems exist at a lower design level, consisting of things that cannot perform their function individually. Rather, subsystems must be integrated together to work [32]. Note that subsystems can be further decomposed into constituent elements, like components or other subsystems in many cases. It is at these lower levels that technologies are applied to comprise or potentially improve a design. Generally, these choices must be rolled up to higher design levels to discern effects of their inclusion upon a design.

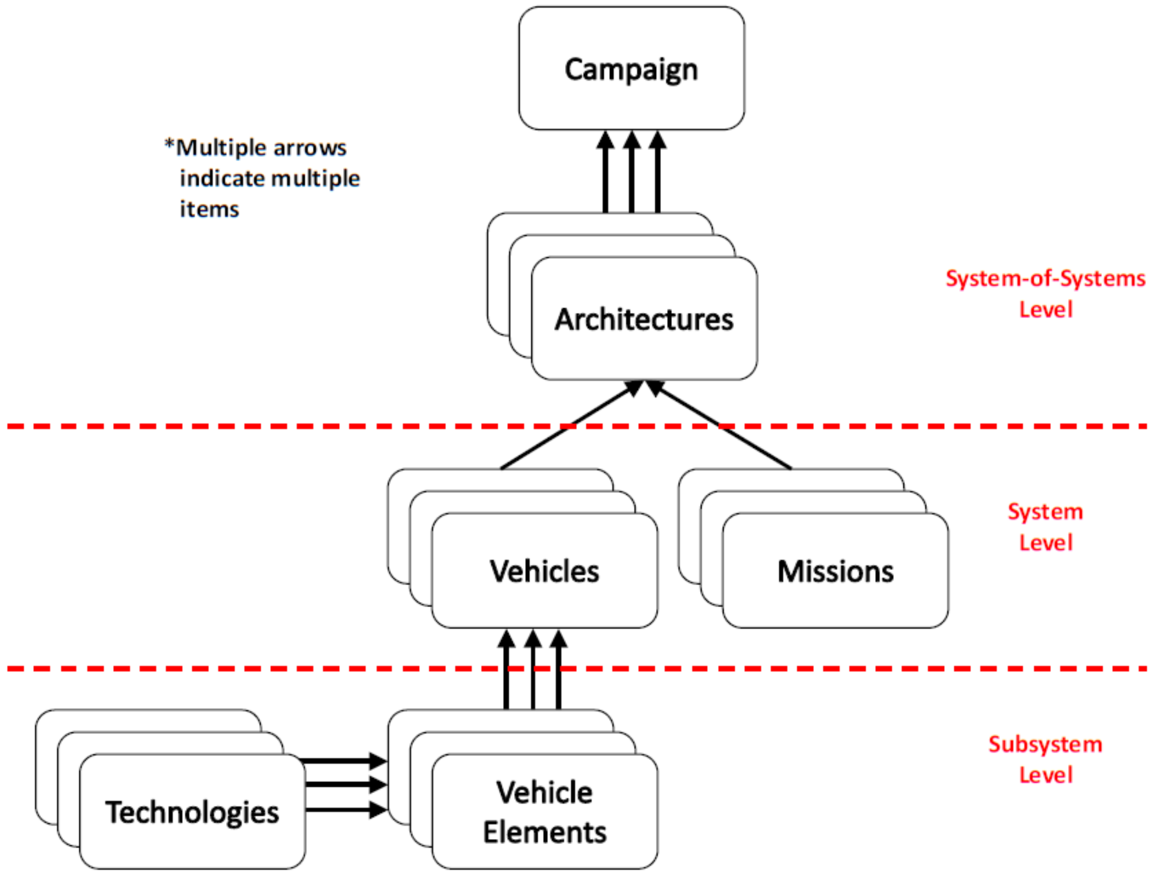


Figure 2-6: A hierarchy of design levels. For non-moving entities like ISRU, 'plant' can substitute for 'vehicle', and 'task' for 'mission' [31].

Systems exist at an intermediate design level. A system can perform a given function on its own, generally comprising a self-contained unit [33]. An exception is generally made for passive umbilicals, like a power cord attached to a toaster or desktop computer. The line between system and subsystem is murky though, and depends on context; software that can run on multiple devices is often considered a system in its own right, though it could not be run absent a device. Different authorities may categorize a design differently depending on the context. A battery could be a system providing power, or a subsystem of a cell phone which itself operates as part of the cellular network SoS.

SoS exist at a higher design level. A SoS is a set of systems that work together to provide a capability that cannot be individually accomplished by any of the constituent systems alone [34]. This is possible due to emergent complexity from higher level interactions between systems. Simply put, the capabilities of the whole is greater than the sum of its parts. Architectures emerge when multiple systems are each given objectives to conduct together as a mission or campaign.

For the purposes of this thesis, [design] concepts discussed are ISRU architectures comprised of many subsystems with associated technologies. ISRU plants are considered architectures instead of systems since many wildly different intermediate functions must be completed to accomplish a goal like producing propellant that is only possible from systems working together. A variety of stakeholders with conflicting desires about the design concept also lends this design problem itself to a SoS engineering mindset [34]. It is desired to examine these concepts at an early stage in the design process, when there is greater flexibility make decisions about designs.

2.1.5 Conceptual Studies

Of course, selecting a design to use is much easier said than done. There is an extensive design space of possible concepts to explore, and many stakeholders with conflicting requirements to consider in down-selecting them. The design space is a set containing all possible combinations of options, from many categories of options. The necessary level of detail to include is also important to determine, as different fidelity representations are best suited for different purposes. Taking all this into account, a design process has been standardized within NASA, beginning with project life cycle pre-phase A: Conceptual Studies [35]. The goal of this stage can be broadly described by injecting new ideas to explore the design space, while also examining constraints on the solution space with preliminary feasibility assessments and draft requirements [36]. It is here that stakeholder requirements are reconciled into constraints upon a design, and the extents of the design space determined.

One way that different concepts in the design space can be compared are trade studies. Trade studies aid the refinement of the solution space in part by providing insight into concept feasibility and the effect of changing various constraints upon the design [37]. Still requirements are not the focus here, only being of interest insofar as they influence the concepts being considered. More of interest is how different concepts can be compared on equal footing, to perform 'apples to apples' trades if you will.

With such a large and relatively unexplored design space, proposed ISRU concepts can be wildly different. The level of detail included can also vary wildly, with some concepts in the literature neglecting to include functionality that other concepts describe in great detail. For example, while the Pioneer Astronautics' Carbonaceous Volatile Asteroid Recovery (CAVoR) System describes the use of augers, pneumatics, and compressors to, the literature on the corresponding concept from Planetary Resources does not specify any material handling techniques [38], [39]. Conversely, Planetary Resources describes the use of multi-layer insulation to wrap tanks of cryogenic liquids after they are refined, though CAVoR does not specify how the extracted NEO resources are stored. A similar inconsistent patchwork of omitted functionality was seen in the eighteen NEO ISRU concepts examined herein. Many of these ISRU architectures appear to be driven by a small set of technologies of interest rather than be designed holistically, leading to this disparate level of design detail. The consequences of this 'technology push' rather than 'mission pull' will be examined in greater detail latter.

2.2 Recent Technological Advances

Though some things have changed, others have stayed the same. When looking at plots such as in Figure 2-2, most decision makers today arrive at the conclusion that to launch larger payloads on longer duration missions, larger rockets are required [16]. These rockets are typically single-use expendable vehicles purpose built for their specific mission, in order to squeeze out as much performance as possible. Furthermore, parts of the launch vehicle and spacecraft are discarded once their job is accomplished, in order to save propellant by minimizing the mass of the vehicle wherever possible at each stage of the mission. The main exception to this mindset is adding redundancy and margins to increase safety and/or reduce risk. To attempt to save money, development of new capabilities is eschewed in favor of reusing hardware developed for other programs where possible. Shortcomings of this approach have been noted for past programs, most famously the Augustine commission on the Constellation program [40].

This risk averse approach to development is a deterrent for ISRU missions, as only a small number of ISRU components have flown in space. Even that concession is debatable, as sources differ about what is to be considered within the definition of ISRU equipment. For example, the environmental control and lift support systems that recycle human waste products back into potable water and oxygen are considered by some to be

ISRU equipment, others do not [3], [29]. In-space manufacturing involving the recycling plastic packaging into 3D-printer filament on the ISS may also qualify [41]. Some might argue that solar panels powered by sunlight technically quality, through most sources only count them if they were manufactured locally [3]. Still, there is agreement that no missions to test utilizing raw materials like rocks have flown in space. Academics have been advocating for the use of space resources since early days of the Apollo program in 1962 with serious design work beginning in earnest in the 1980's as part of Lunar base planning [42], [43]. Unfortunately, little has come of these efforts in terms of flight hardware.

When ISRU is considered for inclusion in future missions, lack of flight heritage often prevents it from flying in space. Case in point, a Mars ascent vehicle with a hybrid motor utilizing oxygen produced from carbon dioxide in the Martian air was considered by NASA to loft the samples collected by the Mars 2020 rover [44]. However, this design was passed over in favor of a lower risk, more conventional solid motor design after relaxing temperature constraints [45]. This is a classic 'chicken or the egg' dilemma. Though the benefits are understood, program managers do not want to shoulder the burden of development on their mission, or overcomplicate the critical path [3].

Still, it does not need to be this way. Launch campaigns have greater design flexibility than single launch missions, as vehicles and/or individual missions in the campaign can build off of each other. Resupply and staging points like habitats are prime examples of this, especially if ISRU is included. This also includes technological development, if not only to apply a system in a new operational environment. A few recent advances of interest in this context include regolith simulants, miniaturization, and reusable space vehicles.

2.2.1 Regolith Simulants

Of particular interest for ISRU development efforts is the advent of commercially available regolith simulants. The use of simulants permits the testing of equipment in a relevant environment, an important aspect of maturing a design and the technologies behind it. Simulants can also provide a proxy to estimate properties that cannot be directly measured, though it is important to note that not all properties can be safely replicated on Earth and different simulants prioritize different properties to accurately simulate in the source material [46].

Though Lunar and Martian simulants of varying fidelity have existed for some time, simulants for NEO are a fairly recent development [47]. Researchers at the University of Calgary reported the first asteroid simulant in 2015, developed in support testing mechanical properties for NASA's OSIRIS-REx mission [48]. Researchers at the University of Central Florida and Deep Space Industries developed a set of asteroid simulants in 2017, which have since been refined [49], [50]. Also, a coalition of researchers lead by the Jet Propulsion Laboratory developed a comet simulant in 2017 prioritizing mechanical and geotechnical properties [51]. The chemical composition and volatile release patterns of these simulants is of particular interest for testing ISRU systems, tests which were not possible until recently.

2.2.2 Miniaturization

There has been increasing awareness of late that ambitious missions can be accomplished in small packages [52]. A range of satellite sizes can be seen in Figure 2-7. Smaller, more efficient electronics have driven this trend of miniaturization, enabling mass reductions of orders of magnitude in space vehicles [53]. Standardization has helped by lowering entry barriers, particularly when CubeSats are considered. CubeSats have done remote sensing missions, host biological laboratories, hoisted solar sails, and even acted as telecommunications relays around Mars [52].

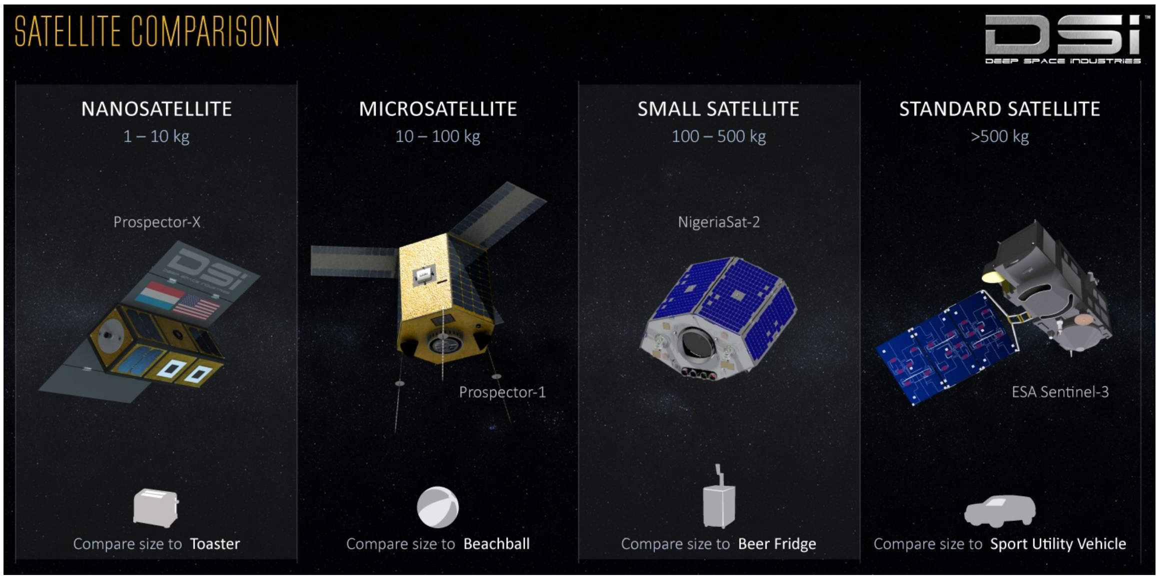


Figure 2-7: Miniaturization of spacecraft (Deep Space Industries, 2016)

When multiple small systems work together, new concepts of operations arise. Formation flying and constellations permit multiple smaller satellites to deliver comparable capability as a larger asset [54]. These capabilities can exceed the assets they are replacing, as in the case of LEO telecommunication mega-constellations. Small systems can also augment the capability of larger systems, such as the deployable heat flow and physical properties package utilized by the NASA InSight mission [55]. Of course, it is the interactions between systems that make these use cases possible.

In the context of ISRU, these smaller networked systems permit robotic pilot plants closer to lab scale, a more manageable first step than the mining villages proposed in the

1980's [43]. ISRU prototypes have also recently been sufficiently miniaturized for inclusion as instrument packages. Two notable examples include the Mars OXygen ISRU Experiment (MOXIE) on the NASA Mars 2020 rover, and The Regolith and Ice Drill for Exploring New Terrains (TRIDENT) on the NASA Volatiles Investigating Polar Exploration Rover (VIPER) [56], [57]. Starting small helps develop the technology, though solutions must ultimately be able to scale to reach demand.

2.2.3 Reusable Space Vehicles

One commonly proposed application for ISRU is supplying propellant for spacecraft, especially reusable ones. There are two main categories of reusable space vehicles considered here, differentiated by campaign level-benefits: launch vehicles and spacecraft. Economics aside, reusable launch vehicles permit an increased launch cadence and decoupling launches from manufacturing [58]. This makes it more feasible to launch larger assets piece by piece. For reusable spacecraft permit increased opportunities for multiple uses of the same hardware during a mission, and/or staging assets in place for use in subsequent missions. In particular, this empowers resupply missions to greatly enhance or extend other capabilities. Taken together, these points show how reusability can help chip away at the cost spiral in Figure 2-1 for multi-mission campaigns.

Still, the main unanswered question with reusable spacecraft is where the extra propellant to fuel them will come from. Reusable launch vehicles can be expected to obtain more propellant from ground support equipment at the start of their next mission, but these capabilities do not currently exist in space. Reusable space vehicles also tend to have greater mass than their expendable counterparts, due to reinforcements for an extended design life and recovery hardware, thus requiring more propellant to operate in the first place. Most proposals today call for refueling spacecraft with propellants launched from Earth's surface on resupply missions, especially if going to Luna [8], [58], [59]. This may be the simplest solution, but it is not the only one.

2.3 In-Situ Resource Utilization in a Supporting Role

The propellant mass to refuel reusable spacecraft does not necessarily need to come from Earth. In fact, it is quite beneficial if it does not. Tsiolkovsky's Rocket Equation (1) holds that spacecraft moving under their own power must expel an exponentially increasing amount of mass as they aim for increasingly energetic destinations with a higher Δv required to arrive [60].

$$\varDelta v = I_{sp}\ a_{g,E} \ln\left(\frac{m_0}{m_f}\right) \tag{1}$$

Similarly, if less payload needs to be delivered, less propellant is required. ISRU introduces the concept that mission supplies can be made during the mission itself [12]. This permits the potential for drastic reductions in launch mass from Earth over the course of a campaign [58], [61]. Note that ISRU goes a step beyond resupply from Earth, as producing supplies in space reduces the need to send additional supplies up a gravity well.

2.3.1 Systems of Systems Problem

Still, it is important to highlight that ISRU activities are rarely proposed for their own sake. Taken in isolation ISRU equipment is both intricate and unproven, with a multitude of steps that need to be executed correctly to be successful [3]. 'Asteroid mining' can fall into this trap, as seeking to return precious metals like platinum to Earth comes across as a ‘warrior without a cause’, due to the imposing technical hurdles and questionable gain from success [62]. Space resources have more intrinsic value in space.

It is better to view ISRU as a force multiplier that supports other systems to augment their capabilities. The real benefits are only seen in the context of other systems, or alternatives. This is analogous to how computer hardware enables software applications [63]. It may not seem worth the effort to develop systems to produce oxygen from the Lunar regolith, unless the reader considers the oxygen would otherwise need to be shipped in from elsewhere to supply the crew of a Lunar habitat. Furthermore this habitat could be constructed with Lunar regolith, if only piled on top as radiation shielding. Something must exist to use the products of ISRU for its inclusion to be justified.

The study of such an idea is a Systems of Systems (SoS) problem by definition, as the capabilities of the whole exceed the sum of its parts. Since ISRU derives most of its benefits from interactions with other systems, a SoS mindset is quite beneficial when examining how its inclusion impacts the mission or the campaign. This also makes ISRU a design problem about interacting and interdependent systems [7]. Figure 2-8 shows how these sorts of relationships can be visualized for a Lunar ISRU concept. Each system has its own requirements, but the capabilities of one system strongly influence what is possible for another system to accomplish. Furthermore, ISRU can be considered a SoS in its own right, since a number of interrelated systems are needed to obtain and process resources into a useable form for the mission.

Though there are many benefits to including ISRU within an architecture, there are also several downsides. The inherent complexity introduces more failure modes to address, and the unproven nature of these systems often makes authorities hesitant to put them on the critical path to success [3]. Putting ISRU on the sidelines can defeat the purpose, as many of the benefits come from replacing supplies to be sent with equipment to produce the supplies. Sending equipment to produce ascent propellant can reduce the amount of mass to be landed on the lunar surface for example, though if the equipment breaks either the ascent payload is significantly reduced or the spacecraft is stuck on the lunar surface.

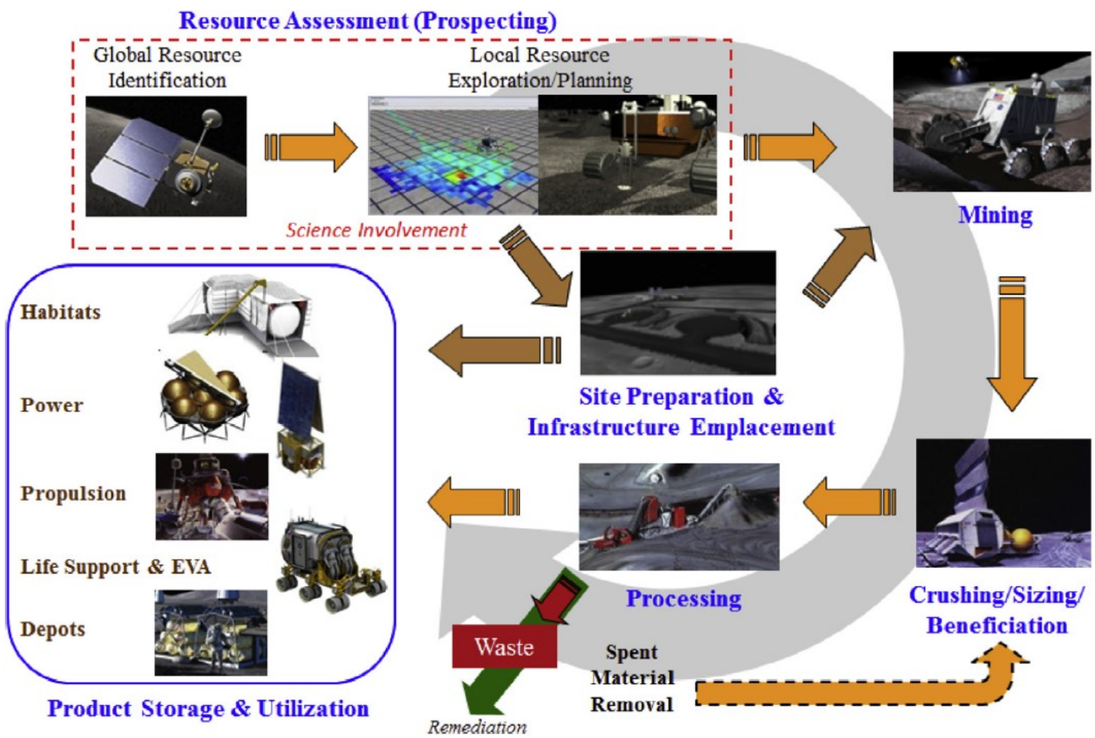


Figure 2-8: Interactions between ISRU capabilities supporting a Lunar habitat [7]

This was one such conundrum faced by the Constellation Program, where proposed ISRU activities were significantly scoped back as development proceeded [64], [65]. The Artemis Program addresses these concerns by conducting initial crewed missions without being dependent on ISRU, then gradually increasing involvement over time, as seen in Figure 2-9 [8]. It is also worth noting that reusable launch vehicles (SpaceX Falcon 9 pictured), reusable crewed landers, and robotic precursor missions to prospect for Lunar ice have been included in the program [8], [66].

2.3.2 Infrastructure for the Future

Of course, the Artemis Program is intended to last beyond the first landings in 2024, with operations until 2028 planned in Figure 2-9. ISRU and resupply from Earth are both key enablers of hopes for ‘sustainable’ operations ‘to stay’ in the latter phases of the Artemis Program [67]. Also of note is the desire to establish staging points, namely the Lunar Orbital Platform-Gateway and possible Artemis Base Camp [68]. Gateway modules are expected to be in compliance with the International Deep Space Interoperability Standards, in order to make the designs be modular and interoperable [69].

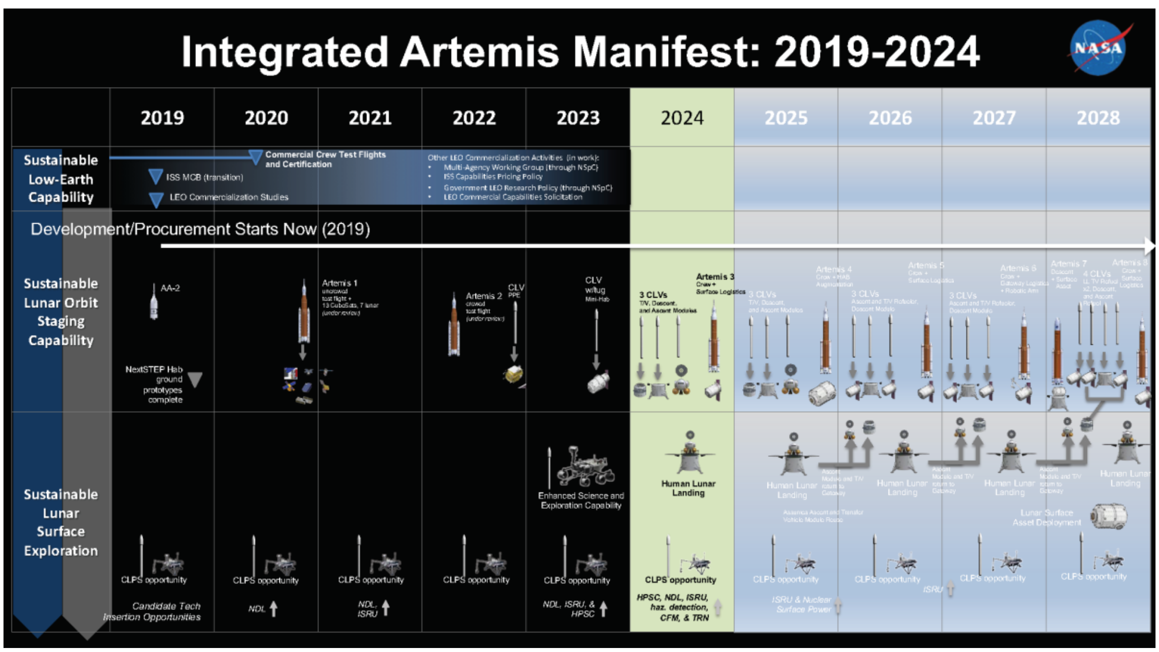


Figure 2-9: Interated manifest for the Artemis program [8]. Note that ISRU demonstration flight projects are planned for 2021, 2023, 2024, 2025, and 2027.

A common thread between these is the desire to put assets in place to build upon. Sunk costs are a very real thing in astronautics, as represented by the emphasis placed on ‘flight-proven’ systems and the longevity of the International Space Station. Bureaucratic inertia and precedent are related concepts in the policy arena. Similarly, NASA appears to be trying to sidestep debate of destinations for crewed exploration with its ‘Moon to Mars’ publicity tact.

Another perspective on this is the desire to put the tools and infrastructure in place to lay the groundwork for follow-up efforts. The goal here is to accomplish enough progress towards an overarching goal in the near term, such that work can still continue towards the goal after political winds or funding priorities shift. The focus is on campaign or architecture objectives, rather than individual missions. This infrastructure put in place can be figurative or literal.

The legacy of Apollo-era spaceflight is both an inspiring and cautionary tale from this perspective, as judged by the achievements of follow-on efforts. Though his plans changed throughout the years, Wernher von Braun’s overarching goal always was crewed expeditions to Mars [70], [71]. Development of a super heavy-lift launch vehicle, lunar spacecraft, and nuclear thermal rocket engine proceeded apace in the 1960’s, all exiting the decade with validated designs. After funding cuts began, the lofty and broad ambitions of the ‘Integrated Program’ follow-on efforts became at odds with each other. The space shuttle ended up cannibalizing funding for the nuclear shuttle, and the space station effort settled for reusing Apollo hardware in the interim under Skylab.

Though the goal of putting boots on Mars has not yet been achieved, 1960’s spaceflight efforts have undeniably left a lasting legacy. For instance, flight proven hardware like the AJ-10 family of rocket engines used in the Apollo service module were also used in the space shuttle, and variants are still used today in the Orion spacecraft [72]. More importantly though, the facilities and research centres built out in the Apollo-era are still around today. NASA maintains and periodically upgrades the assembly and test facilities that make today's missions possible. Crewed exploration missions would be even more delayed and costly than they already are without infrastructure like Michoud, transport barges, the vertical assembly building, crawler-transporters, and launchpad 39A in place.

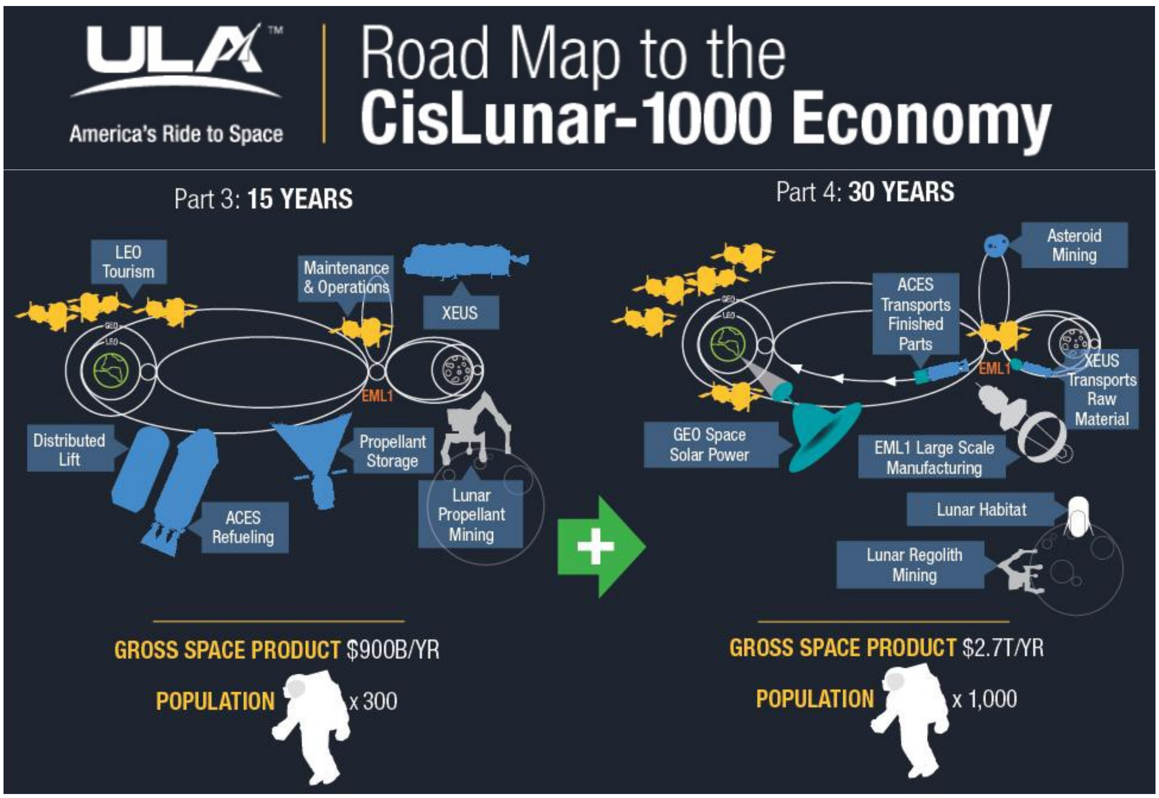


Figure 2-10: Future CisLunar operations utilizing ISRU, as envisioned by United Launch Alliance (ULA). Note that 15 and 30 years from 2015 is 2030 and 2045 [61]

Looking to the future, analogous infrastructure is needed in space to support sustainable exploration and commercialization. Possible examples include reliable supply lines represented by a "transcontinental railway" to Mars, staging points represented by the

Lunar Orbital Platform-Gateway, and/or the processing of space resources [20], [68], [73]. It is this last point that is of primary interest here, due to ISRU being the tipping point to many future capabilities. After all, bases and supply lines depend upon supplies while ISRU can provide them. In this vein, one of the main technology development recommendations made by the Augustine commission was increased investment in the development of ISRU capabilities, especially for propellant production [40]. Much has been written about the value proposition for Lunar derived propellants, and how it enables a CisLunar economy like pictured in Figure 2-10 [61], [74]. Others have also extoled the virtues of NEO ISRU as possible 'gas stations' in space, especially when situated at strategic locations in space like Lagrange points [11]. By harnessing space resources with ISRU infrastructure, the sky is no longer the limit.

2.4 Contrasting Destinations

After recognizing the need for infrastructure, the next logical question is where to build it. A logical postulate is close to the point of use. The following analysis is restricted to crew spaceflight destinations proposed by NASA, since crew missions are typically larger in scope than robotic missions, have lower characteristic energy among deep space missions, and require greater quantities of supplies that could be provided with ISRU. The Artemis Program nominates Luna for consideration, Mars Design Reference Architecture 5.0 (DRA 5.0) nominates Mars, and the Asteroid Retrieval Mission (ARM) nominates NEO [8], [19], [30]. For the sake of argument, Luna and Mars shall both be considered surface destinations. The availability of resources like water shall be discussed latter in § 3.5.2 on Space Resources, as authorities differ on how a resource is identified and deemed recoverable or otherwise useful. This discussion is summarized in Table 2-1.

Table 2-1: Summary of destination comparison discussion, with preferential choices

Category	*Mars*	*Luna*	*NEO*
Δv: to Surface from LEO [75]	≥ 12.5 km/s	≥ 9 km/s	**≥ 4.5 km/s**
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 (MSL)	1 moon of Earth ~5 sites (Luna-Glob)	**17,607+ NEA** [76] **~4 sites each** (OSIRIS-REx)
Water Availability	Subsurface ice (widely dist.)	Pole crater ice (site specific)	**Hydrates & buried ice (target dependent)**

2.4.1 Landing & Weather

To begin, an important consideration is the difficulty of putting assets into place. Notably the harder it is to land assets at a destination, the more perceived benefit there is for supplies produced on site. Mars entry descent and landing is notoriously difficult, with a thin atmosphere and moderate gravity severely limiting payloads [77]. Safe passage to the surface is an issue, with failures all too common. Lunar landings are better understood, though not without issues [78]. The low gravity and near vacuum of Luna help matters from a technical standpoint. When it comes to NEO though, the microgravity environment makes proximity operations closer to rendezvous than descent [79]. The counterpoint to this is that little is known about the cohesiveness and toughness of bulk NEO, and varying degrees of spin and wobble both complicate the ability to remain attached [80], [81]. This means that NEO landings must have finer control and stronger mechanical linkages to remain in contact with the target.

Also of import for arrival is potential acclimate weather at the destination. Day/Night cycles are present on Mars and NEO due to rotation, and Luna from being eclipsed by Earth. This causes energy imbalances between regions, which gives rise to weather. Regolith is blown about in dust storms on Mars, while static discharges is more of a concern on Luna and NEO [82], [83]. Static cling complicates thermal and power management, as well as occlusion by Martian dust and long Lunar nights. Without a strong planetary magnetic field space weather is a concern for electronics, and crew if included.

Synthesizing this information, it can be argued that NEO are a more benign environment for spacecraft than Luna or Mars. These options all have day/night cycles, space weather, and dust concerns. However, NEO have fewer weather conditions to design around and have fewer challenges to land versus surface missions.

2.4.2 Planetary Protection

The prevention of undue contamination is also a valid concern. Planetary protection protocols address this issue by classifying the strictness of measures to be taken by robotic when visiting celestial bodies, according to their propensity to harbor life [84]. Missions to metamorphic and igneous asteroids (as described in Table 3-1) generally fall under Category I according to NPR 8020.12D, with comets and carbonaceous asteroids generally under Category II. Lunar missions also generally fall under Category II. The exception to this is sample return missions which fall under Category V (unrestricted) for NEO and Luna, or Martian flybys which fall under Category III [85]. Martian lander missions tend to be Category IV, with sample return at Category V (restricted).

From this perspective, contamination appears to be of similar concern for volatile rich NEO and Luna. Restrictions are significantly more burdensome for Martian missions. It is also worth noting that samples have been returned from select NEO (Hayabusa), demonstrating industry knowledge to work around these restrictions. There is also a possibility of an additional policy option to assuage development concerns posed by ISRU. This would entail setting aside regions of surface terrain, or subset of NEO, to preserve for future study or posterity. The viability of this hinges on the quantity of options available.

2.4.3 Availability of Options

Though there is only one moon of Earth and only one planet Mars, though each has many possible landing sites considered for missions. 50 landing sites were considered for the Curiosity rover on Mars before down selection, with general regions or entry ellipses specified depending on lander accuracy [86]. In contrast, tens of thousands of NEO have been cataloged as of 2014, as evidenced by Figure 2-2 [21]. Hundreds of millions more NEO, albeit smaller, are suspected to exist but not yet detected. Furthermore, each NEO can also have multiple possible landing sites considered [79]. This greater availability of options increases the possibility that mission planners will be able to satisfy more science and engineering objectives in the same mission.

In addition, Near Earth Objects are by definition more accessible from Earth than other asteroid and comets in the solar system. This means round-trip missions to NEO have lower Δv requirements, with many below that to reach the Lunar surface and return as seen in Figure 2-3 [17]. With a smaller Δv-budget there are a greater number of launch vehicles available to launch a given payload to a NEO, or fewer launches required.

2.4.4 Near Earth Objects in a Supporting Role

Furthermore, this lesser Δv cost to arrive at and depart from NEO opens the possibility of the NEO being a waypoint instead of the intended destination. The minimal escape velocity of NEO also means they have lower energy requirements to reach other destinations in the solar system [11]. This was a key concept behind ARM, in which a small NEO was planned to be brought back to a retrograde lunar orbit for study [87]. ISRU research was planned to be conducted by astronauts on a follow-up mission, with hopes of providing resources "in support of other deep-space missions"; settling Luna and crewed missions to Mars were explicitly noted. Other authorities echo this sentiment [88], [89].

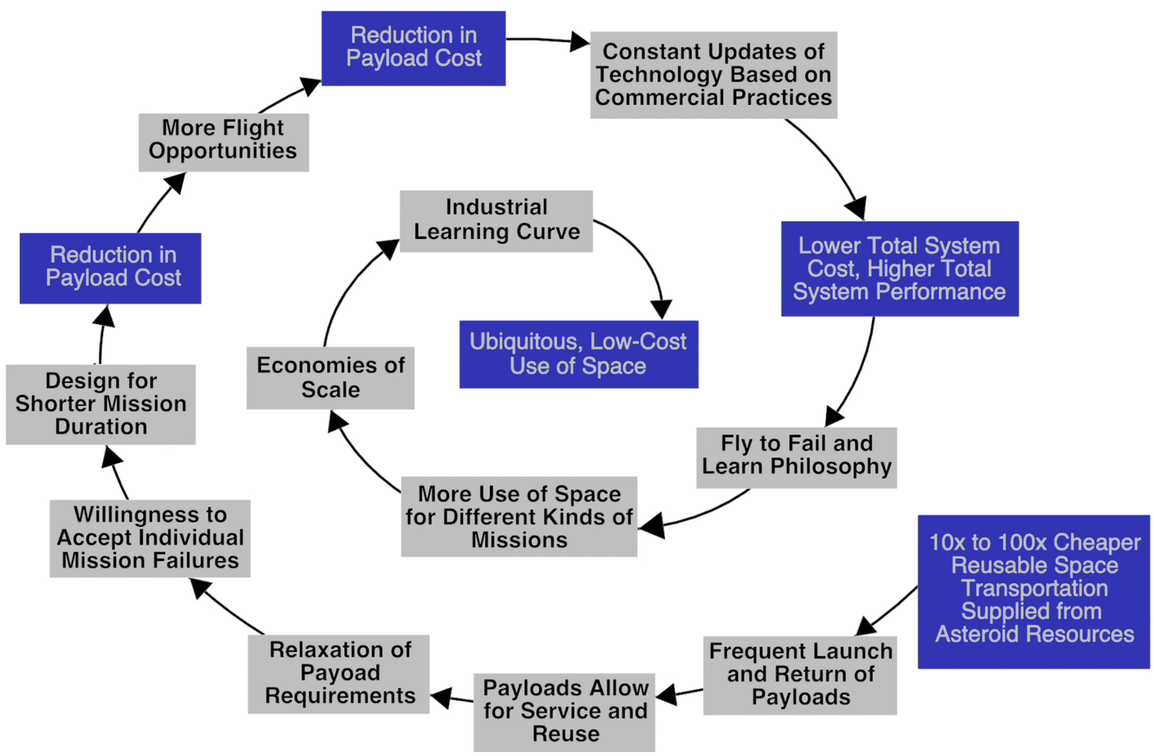


Figure 2-11: Reversing the spiral of increasing costs for space missions [11]

This support could come in two forms: missions stopping at a NEO to take on supplies, or these supplies be sent in advance to staging points along the way. For supplies like propellant, these depots could be considered analogous to 'gas stations' refueling spacecraft to continue their journey [11]. For maximum benefit, reusable spacecraft would be paired with supplies from NEO ISRU infrastructure. Once put in place as part of a larger campaign, unrelated subsequent missions could benefit from both the provided supplies and the technologies developed. Doing so would reverse the cost spiral shown in Figure 2-1 into that of Figure 2-11. This would provide a ripple effect that would reduce the initial mass in LEO required for a given mission over time, thereby increasing access to space through sustainable means. It is important to note that this NEO ISRU infrastructure would need to be designed with standardized connections in mind to reap the full benefits.

2.5 Gaps in Existing Models

As with all grand visions, the devil is in the details. Efforts to advocate for precursor missions to prove ISRU concepts have floundered, in part due to a fragmented field and gaps in existing modeling efforts. There is a severe disconnect between the lower fidelity models used to make architectural trades for space exploration campaigns, and those used to model individual technologies in a larger context. Simply put, there are very different thoughts as to the ease of and means of space resource utilization. Gaps between these camps and within models appear to stem from limitations in scope, or overlooked details.

2.5.1 Unsupported Assumptions

One such type of overlooked detail is unsupported assumptions behind the models. For extremely low fidelity ISRU models of the sort integrated into space logistics frameworks, little consideration is typically given to the proposed mechanisms for ISRU and the validity of assumptions on how they work. Studies associated with the NASA

Constellation program seemingly considered a fixed plant mass to be able to produce an indefinite quantity of a resource, and only note the benefits these resources provide in reducing initial launch mass [90]. Latter treatments assume linear plant scaling, via 'rules of thumb' such as a ratio of plant mass to the mass of resource produced [25]. Another logistics model mentions that electrolysis of water was envisioned, with the mass of the "mining spacecraft" being a free variable [28]. Simplistic prepositions on expected resource flows are the norm, with little to no explanation on why system dynamics or scaling laws presented should be considered valid.

For the models of ISRU, these unsupported assumptions tend to be errors of omission. Some can be attributed to simplifications like making chemical reactions instantaneous and deterministic, or neglecting impurities like sulfur in the processed materials [91], [92]. Whole subsystems are often neglected, as documented in § 4.3.1 on Existing NEO Concepts (esp. Table 4-4). These can be more benign such as neglecting electrical wiring or pipes in lower fidelity models, or more egregious such as not considering power use or thermal management. Even MIT's HabNet neglects to include heaters in its ISRU models, despite setting a high bar in other areas [93], [94]. This oversight is especially notable for phase transition processes, such as heating rocks many hundreds of degrees Centigrade to sublimate volatiles like water.

2.5.2 Point Designs

When combining these systems together or otherwise providing high-level context, the scope of study tends to narrow unnecessarily. Often a particular instance of the ISRU design, or small number of design points, is examined with little evidence that more exist.

This is an issue, since it implies an insufficient examination of design alternatives. TransAstra Corporation's Asteroid Provided In-situ Supplies (APIS^{TM}) is the most fleshed out NEO ISRU concept in the literature, with a scale demonstrator funded for ground test under NIAC Phase III [95]. Available literature on this concept focuses on proving feasibility through technology development, with one sized design published of three mentioned [11], [96]. Additional detailed systems analysis on ISRU tends to be looked at as a potential supporting function for crewed spaceflight, such as in NASA's Mars Design Reference Architecture 5.0 [30]. Physics based modeling of ISRU was implemented, though only select point designs appeared to be made available for trade studies with other disciplines. MIT's HabNet is the exception, including scaling laws for ISRU as part of models for into design and operations of a surface habitat [93].

2.5.3 Microgravity Neglected

Still, better developed models like MIT's HabNet were developed for surface applications, and thus neglect the microgravity environment of NEO. The presence of gravity permits different processing equipment, like hoppers that regolith is scooped into. Other effects of microgravity are less straightforward to design around, such as the lack of buoyancy or natural restoring forces [97]. Many space resource models tend to be developed as offshoots of human space exploration campaigns to Luna and Mars, and this require some adjustment to be used on NEO [30], [90]. Models developed for NEO resources tend to be from companies investigating 'asteroid mining' in some form [11], [81]. Still these models tend to neglect aspects of microgravity operation, such as the need to counterbalance applied forces, rejecting heat in a vacuum, and/or mass transport.

2.5.4 Difficulty of Comparisons

Ultimately though, the main gap in existing ISRU models is the difficulty of comparing designs on equal footing. An emphasis on 'technology push' instead of 'mission pull' has led to concepts diverging into oranges and apples. Researchers have noted this as a pattern where "technology is trying to drive mine planning" for ISRU instead of mission requirements [98]. Even more detailed compendiums, such as the Commercial Lunar Propellant Architecture, appear to be collections of specific 'pet concepts' that are cobbled together [74], [91]. This is complicated by wildly varying levels of detail among systems in the concepts that are represented.

One possible solution to this that has been suggested is the development of a "coordinated nomenclature" to aid comparisons between concepts [98]. The beginnings of a set of options for 'asteroid mining' have been proposed by Sonter (1997 & 2017), Gertsch (1997), Ross (2001), Al Globus (2010), Zacny et al. (2013) and Hellgen (2016), though they each examine a limited set of functional niches and only Zacny et al. and Gertsch provide definitions for terms [80], [99]–[104]. Establishment of a common reference mission and/or baseline design would also help matters. This is of course easier said than done, with numerous applicable technologies and functional niches to explore. Some have started to assess options, but work has remained limited in scope of options considered [105], [106]. Additional shared metrics beyond mass payback ratios (MPR), also known as bootstrapping factor, could help enable apples to apples comparisons. Mass throughput (f)[1/day] has been proposed as a time-specific MPR for net present value calculations [62], [99], [104]. Lifetime embodied energy is one such proposed metric, mirroring cradle to grave sustainable design on Earth [107]. Power mass penalties (*PMP*) [kg/kW] for comparing power and thermal management are another option [108].

2.6 Research Objective

Returning to the focus of research, there is a desire to make this process of comparisons more systematic. Thus, a methodology is sought. Due to the interwoven systems involved in utilizing space resources and the capabilities they support, a System of Systems approach is warranted. By taking these concepts and rephrasing the focus of research into more technical language, the statement below arises. This research objective will be taken apart and expounded upon as the methodology to satisfy it is fleshed out.

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).

CHAPTER 3. METHODOLOGY

With the research objective motivated, the next step is to formulate a general methodology that can later be applied. This is done by taking the key points of § 2.5 on gaps in existing models, and addressing each in turn. The most glaring gap, and the first to be addressed, is the lack of good means to compare In-Situ Resource Utilization (ISRU) System of Systems (SoS) design concepts. The development of a way to reframe many varieties of fruit to all be apples per se is desired, one that is repeatable and extensible to novel designs. This gives rise to the first research question (Q1) of this work:

Research Question 1 (Q1)

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

A logical question the reader may ask is: why focus on conceptual designs? In short, it is the beginning of the space project lifecycle, and one needs to walk before they can run. A large number of ideas have been put forward as to possible technologies that could comprise systems or subsystems as a part of a larger ISRU SoS. Relatively few ISRU SoS concepts have been put forth, with different research groups injecting very different technologies into their designs. Of the published designs, most are missing elements required to function (Table 4-4). This includes all Near Earth Object (NEO) ISRU concepts examined, as discussed in § 4.3.1 on existing neo concepts. Most authorities simply present their ISRU design with expected capabilities, with no attempt to make comparisons. This series of habitual oversights underscores the need for a more systematic approach, as well as input early in the design process.

In addition, with such a large and relatively unexplored design space, the inclusion of screening mechanisms in a method is advisable. Past efforts comparing ISRU concepts cannot discern between technologies considered due to operating primarily at a higher design level, or have significantly down-scoped the set of categories for comparison. An example of the former is space logistics models for campaign level analysis, as well as architectural studies on degrees of ISRU implementation [25], [107]. An example of the latter is asteroid redirection or planetary defense efforts [105]. Thus, this methodology developed should be capable of screening a large number of design alternatives, as well as being sufficiently granular to discern architectural level performance variations from changes in lower level technology choices for inclusion.

3.1 System of Systems Concepts

Taking these observations into a SoS context helps to reveal means that could be incorporated into the desired methodology. Since subsystems comprise systems which comprise SoS, a path emerges to institute traceability between design levels. If technologies are tied to options for subsystems, these choices can be traced within the architectural concept under consideration. Stakeholder desires and other requirements can also be incorporated by means of filtering the options considered. This is not all though. By recognizing that the capabilities of the whole are greater than the sum of its parts, additional avenues for exploration of SoS concepts emerge.

3.1.1 Emergent Phenomena

There are two main emergent phenomena characteristic of SoS that need to be captured in this methodology to ensure that resulting concepts are functionally complete. The first is the interconnections between systems that alter the capabilities those systems must provide. One such way that these interconnections between systems could change capabilities is the scaling of supply to meet demand for some quantity. The system providing supply could simply be scaled up accordingly, or it could be substituted for another system that fulfils the same function but is rated better in the updated operating range. Within an ISRU context for instance, condensing additional water might cause the need to increase the surface area of radiators to reject the excesses heat. Also, the purity of deionized water produced during resource extraction would influence the choice between acidic and alkaline electrolyzers to split water, due to their differing impurity tolerances.

The second phenomenon that must be captured is the uncovering of new functional niches for systems to occupy, which arises when interactions change expectations and create a need for additional capabilities. These new functional niches often stem from the need to facilitate the interactions themselves over a network of some kind. Wi-Fi routers and cell phone towers are a prime example of this, as otherwise mobile devices like cell phones would have trouble connecting to the internet. When it comes to ISRU, an example of this phenomenon is whether material transport systems for granular solids are needed in addition to those for fluids, mainly depending upon the type of excavation and extraction means used. Both of these phenomena need to be captured in the desired methodology to ensure that resulting concepts are functionally complete.

3.1.2 Forms of Comparison

Another advantage of a SoS mindset is the ability to compare concepts at different design levels. Since constituent systems or subsystems with similar functionality can be identified, it is possible to formulate some measure of relative utility for each in their own context for comparison. Even simply identifying analogous elements between existing SoS concepts is a meaningful step in the right direction, given the current state of the field for existing ISRU design concepts.

Taking a step back, it is worth noting that at a fundamental level there are two forms of comparison: qualitative and quantitative. Qualitative aspects can discern differences between allowable options, especially when categorized. Quantitative aspects can assess the performance of a design, and thereby discern the influence of input parameters and other choices. Due to the fact that different options can have different associated parameters, a two stage screening process can be envisioned to make comparisons. The following sections will see the development of systematic screening techniques based upon these two forms of comparison.

3.2 Qualitative Aspects

The use of qualitative methods for comparison permits discernment between notional concepts, even if they are incredibly vague and/or have little associated detail. This ability is incredibly useful in early stages of the design process or project lifecycle. To permit qualitative comparisons on equal footing though, two things are needed: a framework to structure the options considered, and metric(s) with which to compare options.

3.2.1 *Morphological Matrices*

One such framework to structure options is the morphological matrix, as seen in Figure 3-1 [109]. Each row is a category containing a set of alternative options for systems or subsystems that can fulfil the same function. As many rows can be included as there are functions to be included in the SoS, at the current design level. When one morphological option is selected from each category of the morphological matrix, a functionally complete concept is identified. In this way, a large number of unrelated options for elements of a design can be meaningfully structured for consideration.

	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	

Figure 3-1: Selection of an aircraft concept from a morphological matrix [109]

The use of morphological matrices also permits both the categories and options included to be tailored the to suit the design problem at hand. Categories are generally derived from a functional decomposition, in which a design goal is analyzed to find all the intermediate steps that must be taken to achieve it, at a given design level. A use case is translated into required capabilities, which are translated in turn to functions that support their execution [110]. Lower design levels have more functional niches than higher ones. Since technologies are mapped to the subsystem level in Figure 2-6, functional decomposition shall be done to identify required functionality for subsystems. In this way, technologies proposed for use in ISRU SoS can be mapped to morphological options. A review of the literature for both NEO ISRU concepts and related technologies is conducted to identify trends in the functionality included in design concepts as part of the functional decomposition, then used to populate the morphological matrix. By examining a sufficiently wide range of concepts and related systems, it is assumed that the functional decomposition can be made functionally complete. Furthermore, the options included in the morphological matrix can be filtered to only those that work in a microgravity environment. Distinct functionality required for NEO operations can also be uncovered during functional decomposition.

Another advantage of this framework is the ability to easily generate a large number of concepts for comparison, by selecting one morphological option from each category. This is also a systematic process, helping to avoid missing functionality in design concepts, such as thermal management. Selected technologies are mapped to morphological options, which are traceable to an architecture. This enables trade studies through comparisons of morphological options within the design space.

However, to perform a comparison there must be something to compare to. Two concepts can potentially be compared to each other, though it is only a fair comparison if their aims are similar. For an emerging field like ISRU though, there is no legacy flight hardware to use as a point of comparison for most proposed applications. Thus, in addition to crafting a framework for comparison, it is worth finding a baseline to measure concepts against. This baseline should be perceived as the best available; for an emerging field this could mean the most feasible concept for implementation. Feasibility is interpreted here to mean having the fewest identified obstacles to success. From this question of feasibility applied to a mission of interest, the second research question (Q2) can be formulated. Note that In-Situ Propellant Production (ISPP) is a form of ISRU, one that is carefully selected for study in § 3.5 under Q4, and is mentioned here to be consistent.

Research Question 2 (Q2)

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?

3.2.2 Technology Readiness Levels

To narrow down the morphological options to be considered, at least one qualitative basis for comparison is needed. Since technologies are being mapped to subsystem options, it is prudent to consider the maturity of these technologies. Technology Readiness Levels (TRL) are one such metric used to assess this, and are more commonly used than other readiness levels in engineering design [111]. The use of TRLs allows for technologies to be ranked along a scale from 1 to 9 as seen in Figure 3-2, with TRL 9 being routinely used in a similar application. TRLs can also be used as a screening tool, by limiting consideration to the highest TRL morphological options in each category.

However, the formal Technology Readiness Assessment (TRAs) typically used to determine TRLs are not scalable, requiring completion of rigorous checklists of necessary capabilities by parsing through documentation or consulting subject matter experts [111], [112]. Higher TRL levels also tend to be specific to a given mission within NASA, which is an issue for ISRU since no missions utilizing naturally occurring material space resources have flown. It is also worth noting that steps between TRLs are not equivalent, with the required effort to advance the TRL one level varying both within a technology maturation program and between technologies. To overcome some of these limitations, this thesis uses a 'streamlined' TRA. Technologies considered are first defined. Available sources are then scoured to find a representative design utilizing this particular technology,

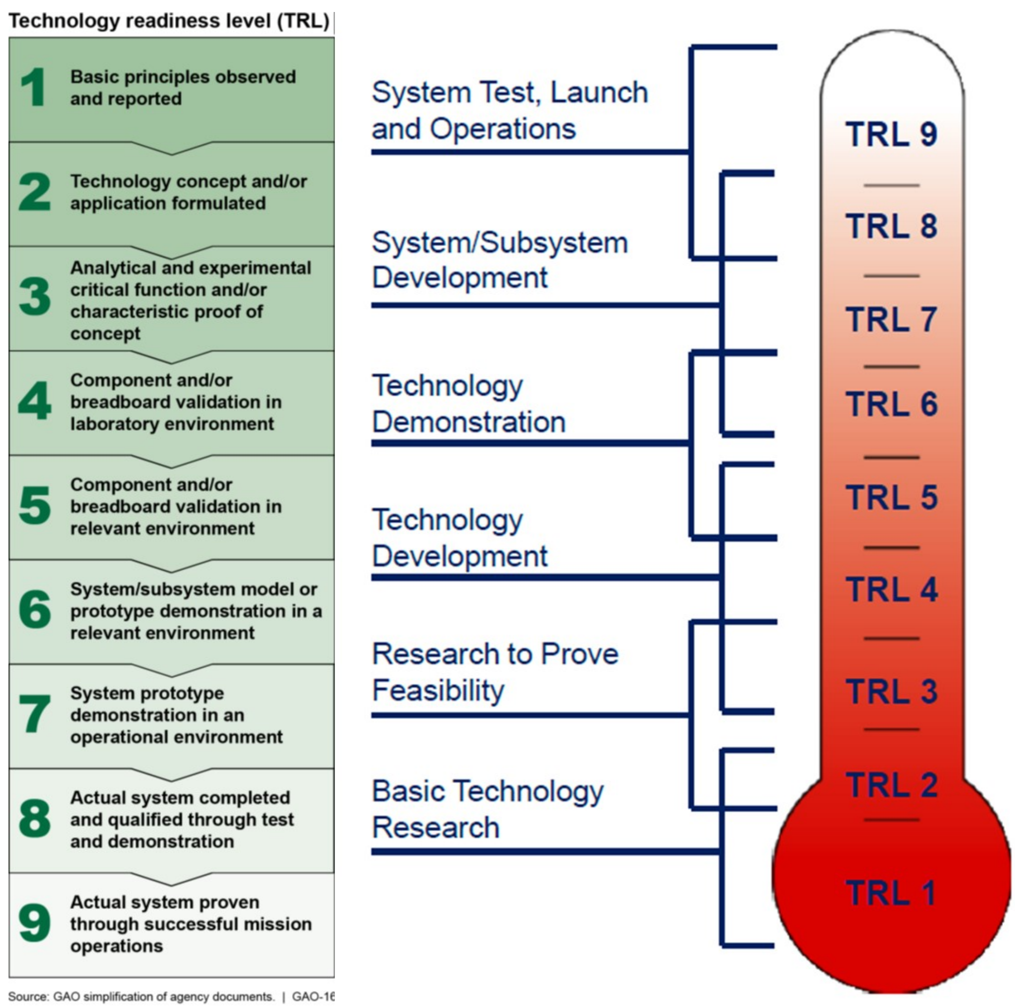


Figure 3-2: Technology Readiness Levels (Images from GAO [112] and NASA [111])

with preference given to recently demonstrated and more mature capabilities. Phenomenological inference is then conducted on this ‘type example’ to approximate the true TRL. Rather than being mission specific, the context of this approximated TRL is instead based upon similarities in the anticipated operating environment. For example, solar panels should be reasonably expected to operate similarly in the vicinity of a NEO as in geostationary orbit, albeit with changes in power output from their distance to the sun. To these ends, values above TRL 5 shall represent established ‘engineering’ and ‘heritage’ technologies rather than ‘new’ ones, in the sense of the NASA TRA study team [111].

In addition, two types of operating environments shall be examined for each technology: microgravity and terrestrial. Microgravity TRLs shall be determined for applications that mirror the physics and circumstances anticipated during NEO ISRU, while terrestrial TRLs shall be the closest analogous application on Earth. Doing so gives a better snapshot of the technology at hand while still keeping the TRA relatively simple. By comparing the pairs of TRLs, technology transfer opportunities and possible data sources for verification of models via analogs can be identified. By examining a pair of TRLs along with their difference, a proxy for advancement degree of difficulty and/or development risk can be found. After all, it is easier to transfer knowledge from a different application than mature a brand new technology.

Ultimately though, it is the microgravity TRL that is proposed to be used here to down-select morphological options within a category. Since TRL is an absolute scale, these morphological options can all be compared simultaneously, instead of in small groups. Many design concepts can also be compared, by counting the number of included options with microgravity TRLs below a given threshold, for instance. Conversely, design concepts can be screened to minimize the number of low-TRL options included. A concept comprised solely of higher TRL options from each category could form a decent baseline for comparison, absent other functionally complete concepts. A set of TRLs corresponding to selected options can also help gauge potential obstacle to success from a development perspective, as higher TRL options should have had more issue ironed out. By summarizing these concepts, research plan 2 (P2) is formed to answer Q2.

Research Plan 2 (P2)
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 a baseline.

3.3 Quantitative Aspects

The insight provided from of such a baseline, determined through the qualitative screening process, would of course be augmented if aspects could be quantified. Note that TRLs are a qualitative metric despite being ordinal, since steps between levels are uneven. Quantitative means of examination tend to be more detailed than qualitative, as more information is needed to compute design performance. Thus, it makes sense for quantitative methods to act as a second stage of screening. This greater degree of detail makes it possible to ask more specific questions during trade studies, such as the impact of different design parameters or the effect of selecting of different morphological options. Performance is primarily assessed on a mass basis, as the main benefit of ISRU is a reduction of payload mass in some form. A secondary basis for comparison is energy use as ISRU can be fairly energy intensive, and the variable heliocentric distance between NEO is anticipated to significantly affect power & thermal management sizing. By considering flows of matter and energy throughout it becomes possible to provide additional output metrics for comparison, such as power mass penalties and mass-specific energy intensity.

3.3.1 Sizing Codes

Of course, evaluating the performance of a design concept is easier said than done. Sufficient granularity is desired to discern between changes in the capabilities of subsystems need to be reflected in the SoS level model for a concept. Since this level of detail is beyond that reasonably expected of hand calculations, computerized means of computation are used. To enable swapping subsystems in line with morphological options, an extensible modular code will be used instead of previous spreadsheet based alternatives that do not scale as well. Subsystems will be translated into functions, systems into code scripts containing functions, and SoS into a case integrator that handles interactions between scripts. A batch scheduler to wrap the case integrator will also be included, to permit varying values between design concepts through a Design of Experiments (DoE).

Trade studies between technologies could be conducted by swapping out morphological options then comparing design performance. Comparing the performance of entirely distinct concepts would also be possible with a sufficiently modular code, if sufficient supporting libraries of functions were developed. Trends from the sizing code could be used to better inform approximations for lower fidelity ISRU models, or captured as surrogate models for use in other fields like space logistics. If a large number of cases is run with properly constructed sets of inputs, higher-level relationships between design parameters and performance metrics can be discerned. Taken together, this envisioned functionality far surpasses the usefulness of point design methods that are currently used.

3.3.2 Model Fidelity

When it comes to the development of ISRU sizing codes though, there is a limited quantity of existing models and surprisingly few prototypes with available data to draw from. Thus, a physics-based modeling approach is needed. Relationships that capture system dynamics and scaling laws of subsystems similar to those used for ISRU in MIT's HabNet shall be included, as well as those for natural phenomena as needed [113]. Note that due to the varying heliocentric distance of NEO, an equivalent system mass approach is deemed inappropriate to size indirect systems like power and thermal management. Quantities like mass flows, power, heat, pressure, and processing time are thus tracked as appropriate to compute the mass of each sized subsystem along with its energy used. Test data from ISRU analog testing by NASA researchers are used where possible to verify the sizing of system models [6], [7]. Comparisons to subsets of sizing codes with similar subsystems like HabNet are also conducted where permissible [93], [114]. When neither is possible, attempts are made to identify analogous terrestrial systems or subsystems to benchmark against. Since there are no existing functionally complete and sized NEO ISRU concepts to use as a benchmark, validation will unfortunately be tenuous at best.

Due to the lack of data for validation, relative comparisons between ISRU concepts and their corresponding morphological options are prioritized. The fidelity of the sizing code will inherently be limited to rough order of magnitude estimates from limitations in the verification and validation process. Thus, the goal will be provide directionally correct results when comparing concepts. This also increases the importance of establishing a baseline to be compared against, such as the set of higher TRL options proposed to be selected through qualitative means.

Due to the physics-based modeling approach, the model is anticipated to have a large number of tunable parameters in many forms. These parameters will be subdivided into two categories: required inputs and optional inputs. Required inputs are those expected to vary significantly between NEO destinations, requiring the determination of a nominal value and a reasonable range in which to vary. Optional inputs are those deemed to only require a reasonable default value. Both of these types of parameters are desirable to be provided to the sizing code. Permitting an arbitrarily large set of inputs permits tweaking default values for each case run, such as testing different assumptions for design margins or for use in sensitivity studies. Doing so also makes the code extensibility to future additions. At the same time though, it is desired to reduce the number of inputs that must be considered during pre-conceptual design to make the process more manageable. The third research question (Q3) of this work summarizes this sentiment.

Research Question 3 (Q3)

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

3.4 A Methodology for Conceptual Comparisons

Through the consideration of both qualitative and quantitative design aspects with respect to SoS in the preceding sections, a methodology for conceptual comparison has been arrived at. A two stage screening process is proposed, based upon a design space structured through the use of a morphological matrix. The qualitative screening occurs first, and is focused on discerning between large numbers of combinations of morphological options. The quantitative screening occurs second, and is focused on discerning between changes in inputs through the identification of trends within performance metrics. These changes can include different input parameters values, or flags to indicate which morphological options should be used. Thus, both qualitative and quantitative design aspects are considered. By rolling up subsystem properties to systems then integrating them together, overall SoS level metrics are computed for comparison. When taken together, this methodology enables a multitude of conceptual comparisons. These points are summarized in conjecture 1, which satisfies Q1 introduced at the beginning of this chapter (Chapter 3).

Conjecture 1 (C1)

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.

Moving to execute this methodology gives rise to four more research questions on how to do so, stemming from the qualitative and quantitative aspects of comparison from resolving Q1. Each of these will be examined throughout the document. To apply the methodology, a specific context is needed in the form of a case study. This is provided by selecting a mission for design concepts to conduct, as examined as part of Q4 in the next section (§ 3.5). This selected mission is used to conduct qualitative screening of options in Chapter 4, with Q2 focusing on the selection of a relatively higher-TRL baseline design. Relevant design parameters meriting additional study are designated as part of Q3 in Chapter 5. Ranges and nominal values for these required inputs to the sizing code are determined, along with development of the sizing code. These threads are tied together in an overarching trade study, which is established in § 3.6 as Q5, further examined in Chapter 6, with results summarized in § 7.2. These relationships are visualized in Figure 3-3.

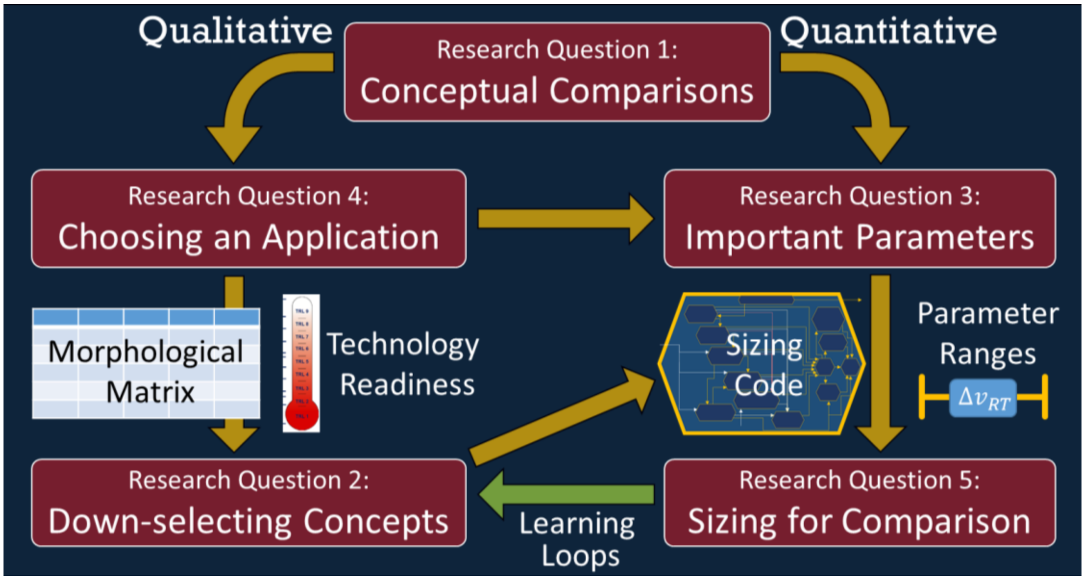


Figure 3-3: Relationship of Research Questions within the Methodology

3.5 Mission Selection

With a methodology established, the next step is to select a mission to contextualize the analysis. From the motivation for this work, it has been established that such a mission should have a NEO as the destination and include ISRU in some form. It is also desired to keep this work relatively grounded and technically feasible, to encourage further study in the near term. Feasible is interpreted here to mean having the fewest identified obstacles to success. These postulates can be summarized by the fourth Research Question (Q4):

Research Question 4 (Q4)
What is the most feasible application for NEO ISRU presently?

3.5.1 NEO Composition by Type

To resolve this research question, a natural follow-up question to ask is: What types of NEO there are to visit? NEO can be categorized by both orbital characteristics and composition, with composition having a greater effect on space resource availability. Orbital characteristics of NEO will be addressed latter in § 5.1.1. Four simplified categories of NEO composition are considered here: igneous ‘metallic’ asteroids, metamorphic ‘stony’ asteroids, carbonaceous ‘primitive’ asteroids, and comets.

Table 3-1: Classification of asteroids by Tholen type into Bell superclasses, with notes on inferred composition and possible meteorite analogs [99]

Bell Superclass	Type (Tholen)	Inferred Mineralogy	Meteorite Analogues	Resources	Metallurgical Properties	Processing Options
Primitive	D	clay, organics	none	volatiles	?? very friable	crush, heat, and separate. CI, CM CR all give >10 % w/w as H_2O, CO_2, CO, CH_4, other hydrocarbons
	P	clay, organics	none	volatiles	?? very friable	
	C	clay, organics	CI, CM (C1,C2)	volatiles	high proportion of matrix / kerogen	
	K	olivine, pyroxene, carbon	CV, CO (C2, C3)	nil?	-------	
Metamorphic	T	?	none	?	-------	-------
	B, G, F	clay, opaques	altered CC’s (CR?)	? volatiles	cemented, hard phyllosilicates and limestone ?some metal	crush and heat to ≈ 800 C; separate volatiles and metal
	Q	olivine,pyroxene, NiFe (grey)	OC’s (- H, L, LL)	NiFe PGMs?		crush and separate using electrostatic or magnetic methods (how to handle bulk metal?)
Igneous	S	olivine, pyroxene, NiFe (red)	S IV could be OCs; pallasites?	NiFe?	hard, finegrained	
	M	NiFe	irons	NiFe		*or* carbonyl process
	E	enstatite	enstatite achondrites (aubrites)	---	-------	------
	A	olivine	brachinites	---	-------	-------
	V	plagioclase, olivine, pyroxene	basaltic achondrites	---	-------	-------
	R	olivine, pyroxene	olivine-rich achondrites	---	-------	-------
	(M?)		enstatite chondrites	NiFe	hard	crush and electrostatic separation

These categories were chosen to include the three Bell ‘superclasses’ described Table 3-1 in addition to comets [115]. Note that the Bell superclasses, are a condensed form of the Tholen type classifications formed by analysing differences in reflected light from afar via spectroscopy. Though the Tholen types have been re-examined over the years and re-cast into the 24 Bus-DeMeo taxonomic classes more commonly used today, the Bell superclasses remain as valid groupings for consideration [116].

This list is ordered by increases in suspected volatile content like hydrocarbons as in Figure 3-4, though little is definitely known beyond the presence of select elements and molecules from absorption bands [117]. A few missions have collected samples, but with significant variation between spectral classes few generalizations can be made. NASA Stardust collected comet tail dust, ESA Philae examined a comment in-situ, and JAXA

Hayabusa returned with samples from a metamorphic asteroid [118]–[120]. Two sample return missions to carbonaceous asteroids are underway at press time, JAXA Hayabusa 2 and NASA OSIRIS-REx [79], [121]. Suspected mineralogical data for other classes stems from comparison to meteorites, albeit modified by atmospheric re-entry, and modelling to fit the data [122]. This information from spectroscopy, meteorites, and sampling is synthesized together to determine what combinations of terrestrial materials can act as NEO regolith simulants [49], [50].

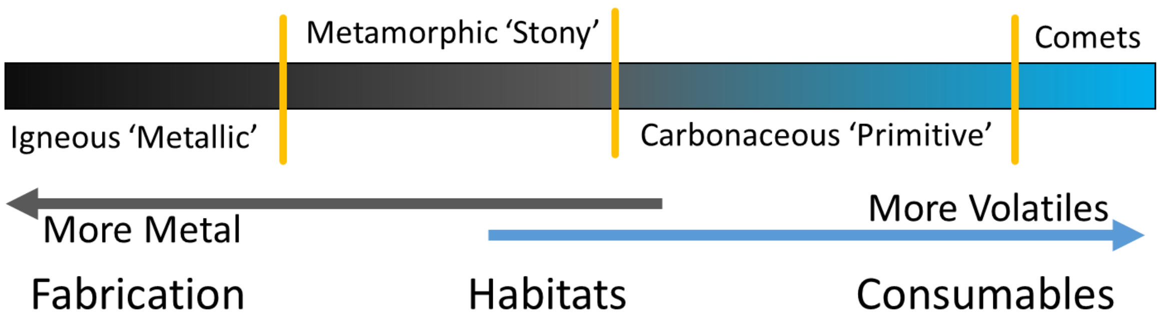


Figure 3-4: A spectrum of simplified NEO composition categories, and posible uses

From these lines of research, some thoughts of asteroid composition can be made. A key distinction to be made is between volatile compounds that readily off-gas when heated, and non-volatile materials that alter allotropes or crystallinity instead. Comets tend to have proportionally higher volatile concentrations, since they are nudged in from the outer solar system where there is a lower propensity for off-gassing [123]. Carbonaceous or 'primitive' asteroids are also thought to have undergone less heating throughout the years, perhaps due to lower concentrations of radioactive aluminium and iron isotopes [124]. These carbonaceous asteroids are suspected to be similar to carbonaceous chondrite meteorites, hence the name [125]. Metamorphic or 'stony' asteroids are assumed to have proportionately more silicates and fewer volatiles than carbonaceous ones, with several minerologies thought to exist from varying degrees of heating and metamorphism [124].

Igneous or ‘metallic’ asteroids are thought to be those that melted and latter re-solidified, undergoing the greatest heating of Bell superclasses. With some knowledge of NEO composition a picture begins to emerge of what might be found useful, with different types of ISRU taking better advantage of volatiles versus metal ores.

3.5.2 Space Resources

A second logical follow-up question to ask is: What constitutes a space resource? After all, the various forms of ISRU shown in Figure 2-5 can only be conducted if the necessary resources are present, and the technology has been developed. This question can be separated into several thrusts: how space resources are identified, what resources are recoverable, and relative utility in the context of a mission.

First off, authorities differ on what constitutes a resource in space. This was briefly alluded to towards the beginning of Chapter 2 – Motivation on page 18 as part of the discussion on flight heritage ISRU (or lack thereof). The narrowest definition is naturally occurring species of matter at recoverable concentrations, as typified by companies interested in mining related activities like in Figure 3-5 [103]. A slightly broader definition is all naturally occurring matter in space, as typified by space habitat researchers [3]. This stems from acknowledging that bulk regolith can have merit, usually as radiation shielding or feedstock for sintering into structures. By broadening the definition once more, otherwise ‘discarded’ materials are included [1], [29]. Retired satellites and crew wastes fall into this category, with recycling efforts sometime proposed as a value added space debris removal technique or avenue for commercialization [126]. The broadest definition admits natural conditions in addition to matter as operationally useful space resources [4],

[7]. These environmental conditions stem from the location of systems. The presence of vacuum, microgravity, and perpetual light or darkness each affect the operation of equipment; ISRU concepts can take advantage of this to improve their effectiveness. An example of this is the separation of functionality between permanently shadowed regions and well illuminated areas atop crater rims near the Lunar south pole in ISRU concepts under development for possible inclusion in the Artemis Program’s latter phases [127]. This work will use the final, broadest definition of space resources for similar reasons.

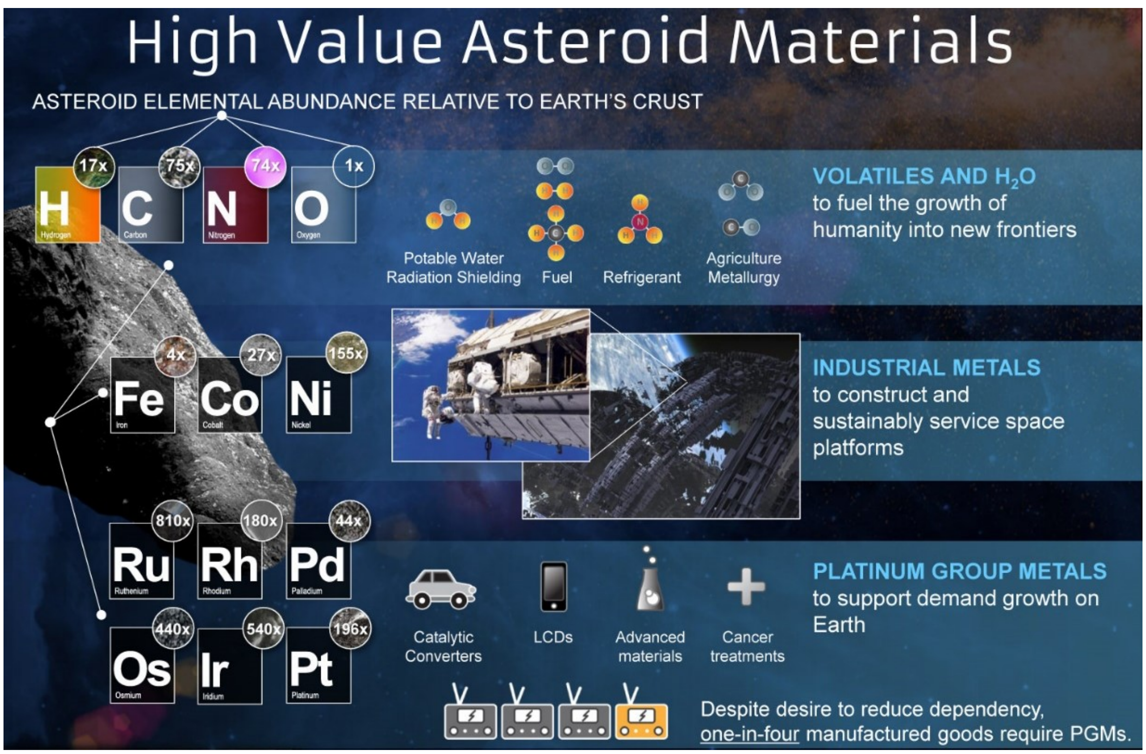


Figure 3-5: High value asteroid materials (Planetary Resources, 2013)

With this definition, the next step is to identify space resources present on NEO in operationally useful concentrations. Potentially advantageous natural conditions include vacuum, microgravity, static electricity, and sunlight. Higher orbits can have perpetual sunlight, though maintaining perpetual darkness in eclipse is unlikely to be feasible. Discarded matter is limited to waste from the mission conducted, as it is assumed that the

NEO has not been visited before, or only by assets sent in advance that will also be used during the mission (e.g. reconnaissance orbiter). Naturally occurring matter is limited to ejecta and regolith. NEO regolith is composed of volatiles, minerals, and metals, with the relative proportions depending on the type of NEO. Platinum group and rare earth metals are also known to be present in the regolith, though ore characteristics are unknown [128].

After space resources are identified, the next step is to ascertain which are sufficiently recoverable or otherwise available to be used operationally. Through a high level deductive analysis, observations about use cases for NEO resources can be made:

- Metal oxides and silicates could be used to produce oxygen [129].
- Rare earth and platinum group metals are only known to be known in low concentrations within NEO regolith, with the distribution and grade of ore unknown [130]. Thus, their recovery is deemed too speculative for consideration at this time.
- Metals are sufficiently present for in-space manufacturing to be a possibility, especially for igneous asteroids [130]. Sintering regolith to build/encase structures is also a possibility, though off-gassing volatiles could cause defects [131].
- Volatile extraction permits producing a range of hydrocarbons [130]. These could be processed into consumables such as potable water, breathable air, and simple propellants [7]. Comets or carbonaceous asteroids have the best chances for recoverable concentrations.
- Comets tend to be few in number and traveling fast when closer to the sun [123]. Δv likely higher to reach, and comet tail may interfere with operations.
- Microgravity is more likely to hinder efforts than help them, due to the need to adapt systems and the challenge of testing them in a representative environment.

From these observations the semblance of a use case continuum emerges, as in Figure 3-4. NEO with more volatiles like carbonaceous asteroids are likely better for consumable production, while those with fewer volatiles like igneous asteroids are likely better for working with metals. In-between are metamorphic asteroids, where both consumables and metals are somewhat advantageous to examine. Thus, the choice of which type of NEO to visit can be tied to the supplies desired from ISRU. If consumables such as propellant are desired, carbonaceous asteroids are more suitable. If manufacturing spare parts comprised of metal, igneous asteroids are more suitable. If crewed habitat is anticipated, a metamorphic asteroid might be advisable to supply consumables as well as construction materials for the habitat. Still it is important to note that significant uncertainties remain about NEO composition, and that upon a more detailed analysis classes of NEO within the types discussed here could very well be found to differ from the trends discussed.

3.5.3 Crewed or Robotic Mission

When considering the role for ISRU in a mission, it is important to define whether the mission is crewed or robotic in nature. Consumables may be produced and parts manufactured using robotic means, though inclusion of a habitat inherently implies crew may be present. There are both advantages and disadvantages to having people present.

From a programmatic standpoint, crew campaigns tend to be larger in scope than robotic ones. Systems tend to be sized larger due to greater payloads and required return trips, increasing the benefits to including ISRU in the architecture [40]. Furthermore, the larger budgets requisitioned for crewed missions provide opportunities to fund ISRU development efforts along the way. Still, the real issues occur once in the field.

Maintenance, reliability, and operations for ISRU systems are all major concerns that remain unaddressed at present [98]. Crewed operations offer a major boon, as people are better at troubleshooting and are more adaptable than robots. Still this is a double edged sword since the presence of crew also raises the consequences of failure. More redundant and fault tolerant systems are required in the design to achieve human rated status. This is a glaring issue for ISRU, as all equipment proposed for use is inherently experimental and unproven for spaceflight due to the absence of flight heritage designs (life support excluded). Testing requirements to ensure supplies produced via ISRU are fit for human consumption may also be fairly onerous. Thus from a programmatic standpoint, ISRU can only be used in non-critical path aspects isolated from critical systems as part of a crewed mission, or first be proven to function as expected during robotic missions [3].

Such a robotic mission would be categorized as a technology demonstration mission. A primary mission objective would be to test and de-risk ISRU in an operational environment, thereby increasing their TRL [3]. This could involve testing of prototypes in orbit with regolith simulants as proposed by TransAstra corporation, or a smaller scale pilot mission to a NEO [63], [96]. This sentiment is echoed by authorities in the field, as shown in Figure 3-6 [117], [132]. It is intended that observations on NEO of interest from afar leads to reconnaissance orbiters and surface probes, followed by a test mission for ISRU. Note that there have been five sampling missions to date of NEO: two to comets (NASA Stardust and ESA Philae), one to a metamorphic asteroid (JAXA Hayabusa), and two to ongoing missions to primitive asteroids (JAXA Hayabusa 2 and NASA OSIRIS-REx) [79], [118]–[121]. A robotic technology demonstration mission to these sampled NEO, or ones suspected to be of similar composition, would be a logical next step towards the development of NEO ISRU capabilities.

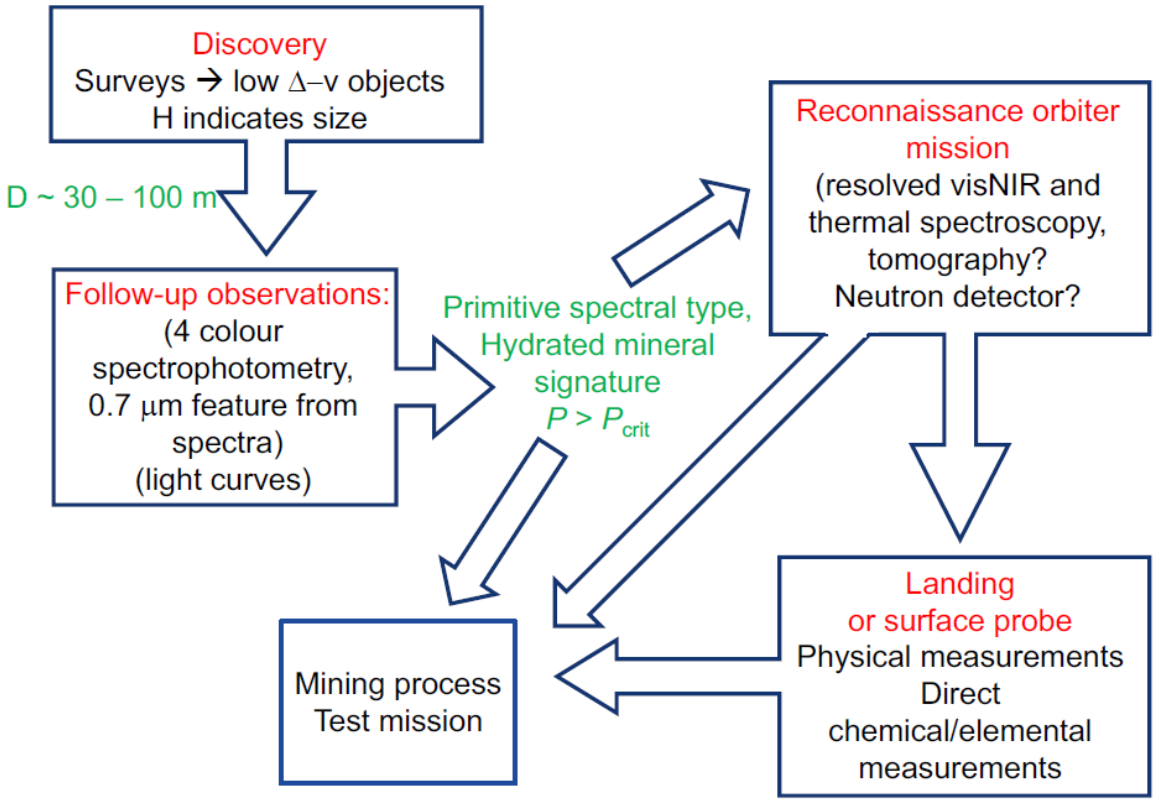


Figure 3-6: A sequence of objectives to initiate ISRU on a particular NEO [132]

With this added information, we return to the discussion of which use case for ISRU would be advantageous to include in a mission to NEO. Support for a habitat is out of consideration, since habitats tend to be accompanied by crewed and are on the larger end of space missions proposed. If consumables such as propellant are desired, primitive asteroids are more suitable. If manufacturing spare parts comprised of metal, igneous asteroids are more suitable. If crewed habitat is anticipated, a metamorphic asteroid might be advisable to supply consumables as well as construction materials for the habitat. In space manufacturing capabilities may be able to be tested remotely on a smaller scale, though no ground truth sample data is available on members of the igneous superclass that are likely preferable for it. The production of consumables may also be able to be tested remotely at pilot scale, though in this case work on securing sample data on the primitive asteroid types likely preferred for it is in progress.

Thus, some form of consumable production via NEO ISRU is preferable for testing at pilot scale. Consumables commonly considered to be produced via ISRU include potable water, breathable air (oxygen and/or nitrogen), and simple propellants [7]. Of these options breathable air can be reasonably eliminated for a robotic mission, as there is no crew present to use it, or depending upon receiving the supplies elsewhere.

3.5.4 Policy Angles

Another important consideration for mission selection is what is currently permitted under institutional and international policies. First and foremost among these is the 1967 Outer Space Treaty [133], [134]. This treaty holds that territory cannot be claimed by nation states, and by extension perpetual property rights cannot be conferred. Activities in space for peaceful purposes are intended to be unrestricted, though exclusion zones are permitted around current assets for safety reasons. All payloads launched from Earth must also be registered as the responsibility of a national government under the Space Liability Convention of 1972 and the Registration Convention of 1976, though the status of space resources after being extracted is uncertain. Select nations such as the United States and Luxembourg have tried to assert that the presence of assets can permit mining claims and possession of resources can confer ownership, though these provisions have yet to be tested. Thus significant legal uncertainty exists on top of technical uncertainty, limiting the viability of commercial business cases for ISRU at present.

For this reason, measures of cost and discussions of financial return on investment may not be the most persuasive arguments to promote ISRU. The primary alternative to space commerce is the conduct of science and exploration, usually by government entities. Shipping supplies produced from NEO elsewhere to support exploration campaigns would likely have an easier business case than commercial extraction, though who would be entitled to request use of those resources also has some degree of legal uncertainty at present. When it comes to science missions, planetary protection protocols are an important consideration here for mission design, as discussed in § 2.4.2 – Planetary Protection. To recap, landers on carbonaceous asteroids likely fall under Category II, and missions involving material sent from NEO likely fall under Category V (unrestricted), especially if traveling back to Earth.

3.5.5 Selected Mission

With these constraints in mind, a sample return mission of some form would be a good choice for study. Since the objects returned would be scientific in nature, the aforementioned legal issues on possession can be sidestepped as the samples could be shared. The use of ISRU techniques could also drastically increase the mass of the sample capable of being returned to Earth, especially if the consumable produced on site is propellant. The spacecraft arriving at the NEO could be refilled with propellant for the return trip, permitting reuse of hardware. Development of the required ISRU systems could be harmonized with science experiments on the properties of NEO regolith. Experiments to test asteroid formation theories by monitoring regolith before and after it is heated would especially be of interest. Note that proposed biological processing methods like bacteria digesters would be excluded, as they are likely to violate planetary protection protocols.

In this way, a heavily instrumented pilot plant producing propellant deployed to a member of the carbonaceous asteroid superclass as part of a sample return mission could be both a technology demonstration mission for ISRU and a science mission investigating asteroid formation theories. This type of ISRU is called In-Situ Propellant Production (ISPP), leading to conjecture 4 which resolves Q4.

Conjecture 4 (C4)

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

By logical extension the selected mission will be a sample return mission, while also functioning as a technology demonstration mission. A single un-crewed outbound trip with a single return trip is desired in the concept of operations, in order to simplify the analysis and tailor it to focus upon examining ISPP SoS design trades at the conceptual level. In addition, the analysis will assume a burn to enter Low Earth Orbit (LEO), avoiding the need to model entry, descent, & landing.

Selected Mission

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).

The proposed program name to develop a design that accomplishes this mission is “Sample return from Near earth object with In-situ Propellant production Technology demonstrator” (SNIPT). Science objectives could include the study of NEO regolith with a focus on composition changes under heating, asteroid composition versus depth, and to test theories on asteroid evolution and/or formation of the early solar system.

3.6 Case Studies Considered

With the mission selected, it is time to identify what aspects of the design concepts to fulfil the mission would be the most impactful to study at the conceptual level. Since ISPP is being conducted, which propellant the SoS should produce is an interesting question with far ranging implications. Some propellants are more difficult to refine than others necessitating additional equipment, while differing specific impulse between propellants affects the amount needed and therefore ISPP sizing as well. This question lends itself to the methodology nicely, forming the fifth research question (Q5).

Research Question 5 (Q5)

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

The use of a morphological matrix permits qualitative comparison of designs, with differences between these designs assessed quantitatively through varying input parameters in experiments. Research plan 5 summarizes Figure 3-3 and the methodology.

Research Plan 5 (P5)

Construct morphological matrix, using functional decomposition. Down-select concepts qualitatively for each propellant considered using TRLs in line with Q4. Determine input parameters in line with Q5, then create modules in sizing code to correspond with selected concepts. Verify and validate as appropriate, then screen values using quantitative methods.

Two experiments are proposed: to investigate the effect of NEO orbital characteristics and composition upon the choice of propellant to be used. Hypotheses are formulated here, with further discussion inn Chapter 6 on case studies.

Several different propellants are envisioned as being feasible to be produced from volatiles extracted from NEO regolith. Chemical propellants are the most common proposed to be produced, with hydrogen for electrical or nuclear propulsion sometimes mentioned as well. Note that mass drivers will not be considered here, due to an extremely low specific impulse and space debris concerns. Extraction of water from ice and hydrated minerals is of particular interest, since it could be used on its own as steam monopropellant or split into hydrogen-oxygen bipropellant (hydrolox) [11]. If only hydrogen is desired, a large quantity of excess oxygen is generated. Rocket engines that run fuel rich have a similar issue, but to a lesser extent. Methane-oxygen bipropellants (methalox) could be also be produced. Though the specific impulse of methalox is lower than hydrolox, its rocket engines tend to burn closer to stochiometric and carbon compounds can be used, potentially increasing feedstock availability [135]. Note that the production of more complex compounds like kerosene is unlikely, since it takes significantly more complex equipment and specific impulse decreases as a result. With this information in mind on the degree of refining versus relative specific impulse, hypothesis 5 (H5) is formulated. H5 is broken down into H5.1 and H5.2, to better define ‘demanding target’ for analysis.

Hypothesis 5 (H5)

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.

3.6.1 Experiment 1: NEO Orbital Characteristics

Discerning the effects of varying NEO orbital characteristics upon the sized ISPP mass by propellant type is the focus of experiment 1 (§ 6.1). A more demanding target in the sense of orbital characteristics is thought to be delineated by higher change in velocity to return (Δv_{RT} [km/s]), as there exists an exponential relationship between it and spent propellant mass in the rocket equation (1). This statement is formalized in hypothesis 5.1.

> **Hypothesis 5.1 (H5.1)**
>
> 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.

3.6.2 Experiment 2: NEO Composition

Discerning the effects of varying NEO composition upon the sized ISPP mass by propellant type the focus of experiment 2 (§ 6.2). A more demanding target in the sense of NEO composition is thought to be primarily determined by the concentration of resources in ore. Since hydrogen is required for all propellant types considered and oxygen is required for 3 of the 4, water is deemed the primary feedstock for propellant production and sizing will likely hinge upon its availability. This assumption is captured in hypothesis 5.2.

> **Hypothesis 5.2 (H5.2)**
>
> If sized ISPP plant mass sensitivity to NEO composition is analyzed, then the availability of water will have the greatest contribution to variability.

Note that methalox is a special case, since it also requires carbon as a feedstock. It is hypothesized that this additional source of matter will make methalox more robust to changes in NEO composition, and also increase its mass payback ratio on average.

CHAPTER 4. QUALITATIVE DESIGN ASPECTS: MORPHOLOGY OF THE DESIGN SPACE

Now that a methodology has been formulated and a mission selected provided for context, execution can begin in earnest. The goal here is to get a feel for the extents of design space, then obtain a functionally complete baseline for comparison. This baseline can be obtained by assuming that a higher Technology Readiness Level (TRL) correlates with increased probability for mission success. This goal can be framed as research question 2 (Q2) restated below, and will guide the investigation conducted in this chapter.

Research Question 2 (Q2)
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?

With feasibility framed as a question of which morphological option has the highest TRL in a given category, research plan 2 can be followed as outlined in § 3.2 to find the desired baseline concept and thereby answer Q2 satisfactorily.

4.1 Review of Functionality for ISRU

To gather sufficient information to perform a functional decomposition, it is prudent to examine ISRU concepts that have been proposed by other authorities. A brief look at notable existing concepts for Mars, Luna, and NEO shall be given, with a focus on the functionality proposed to be included. A few notes on how functional niches within free-flying spacecraft are important to ISRU SoS as well are also given.

For NEO ISRU in particular, a wide variety of designs were noted. Fourteen distinct NEO ISRU concepts were found, and treated individually within Appendix A – Review of Existing Concepts. Design iterations and rescaled versions were generally understood as the same concept evolving over time as ideas were fleshed out, instead of being distinct concepts in their own right. Commonalities between concepts proposed by different research groups were significantly less than originally anticipated, indicating an extensive design space to be explored and little agreement within the field on a typical solution. Particularly notable was severe disparities in the fidelity of solutions described between functional needs that were identified.

In its most basic sense, In-Situ Propellant Production (ISPP) was recognized to consist of locating resources of value, methods to acquire said resources, processing them into a useable form, and an energy source to power the process. The two main commonalities noted between proposed design solutions were a desire to harvest water via heating, and a desire to utilize sunlight to the greatest extent possible. Similarly, the idea of using a solar thermal concentrator to spall rock and release volatile gasses (termed ‘optical mining’) was one of the few ideas that appeared to be cross-pollinated between designs [81], [89], [99]. From this observation, hypothesis 2 was formed.

Hypothesis 2 (H2)

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.

4.1.1 Concept Capabilities

Due to the relative disorganization of NEO ISRU concepts, more mature concepts for ISRU on Lunar & Mars are examined to provide structure. Of the concepts put forward, those put together to complement NASA's crewed exploration efforts to surface destinations are the most thought out, and therefore the ones to be examined here.

Table 4-1: TRLs for ISRU options considered in NASA DRA 5.0 [30]

Technology	Current TRL	Dev. Time to TRL 6 (years)*	Dev. For Lunar Campaign (Y/N)
Mars Atm. Acquisition and Separation			
CO_2 Freezing	3–4	2	N
Microchannel adsorption bed	3	2	N (for ISRU)
Mars Water Acquisition			
Excavation unit	2–3	3	Y (similar)
Hauler/dumper mechanism	2–3	3	Y (not yet)
Surface mobility unit	5–9		Y
Soil processing reactor	2–3	4	Y
Carbon Dioxide Processing			
CO_2 electrolysis	4	3.5	N (for ISRU)
Microchannel Sabatier reactor	4	2	N (for ISRU)
Microchannel RWGS reactor	4	2	N (for ISRU)
Integrated Sabatier/RWGS	4	1.5	N
Water Processing			
Water electrolysis	6–9	1.5	Y
Microchannel water/gas separator	4	2	N (for ISRU)

When it comes to efforts to put boots on Mars, the most comprehensive study to date by NASA is the Human Exploration of Mars Design Reference Architecture 5.0 (DRA 5.0) and its addendums [30]. This report includes several chapters assessing capabilities of ISRU SoS for Mars applications. ISRU was primarily considered to produce propellant for the Mars ascent vehicle, with options to produce only oxidizer or both oxidizer and propellant considered. Technology Readiness Levels (TRLs) were assessed for candidate technologies selected for inclusion in concepts, as indicated in Table 4-1. Note that trade studies in DRA 5.0 appeared to be more oriented as to determining the degree to which ISRU should be included in the architecture, rather than which ISRU related technologies that could fulfil a function were more beneficial to implement.

One proposed means considered to produce oxygen from the Martian atmosphere is shown in Figure 4-1 [30]. There are three main functions that can be identified from this process schematic: extracting carbon dioxide from the Martian atmosphere, refining carbon dioxide into oxygen, and storage of produced oxygen. The inclusion of duplicate flows and an extra system of comparable size is notable for both redundant hardware and oversizing of capacity to increase reliability. This process is also site agnostic, with resources extracted from the atmosphere, and byproducts simply vented.

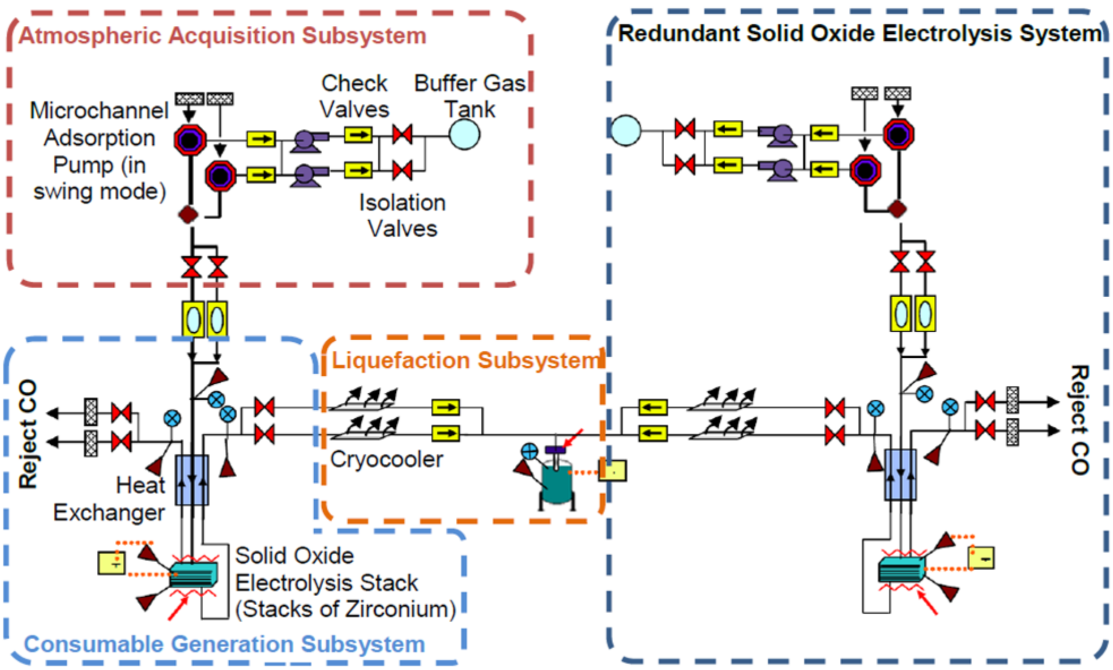


Figure 4-1: Process schematic for an ISRU plant producing oxygen from the Martian atmosphere as part of NASA DRA 5.0 [30]

A separate means to harvest water to produce propellant was also considered to supplement the carbon dioxide processing [30]. This process included four main functions: excavating regolith, extracting water from the regolith, refining the water into propellant, and storing the resulting propellant. Also notable is the need for ‘mobility units’ to transport regolith and separators to isolate the water from other evolved products. Such a process involving processing rock was stated to include less mature technologies than atmospheric processing in Table 4-1, though application of techniques to Lunar ISRU was noted.

When it comes to Lunar ISRU a greater number of use cases for space resources are generally considered as per Figure 2-8, though these resources are generally limited to oxygen or water extracted from the Lunar regolith [7]. Though leveraging ISRU within the Artemis Program has high level administrative support as per Figure 2-9, the role for ISRU to play has not been fleshed out publicly beyond precursor prospecting missions like the NASA Volatiles Investigating Polar Exploration Rover (VIPER) [8], [56].

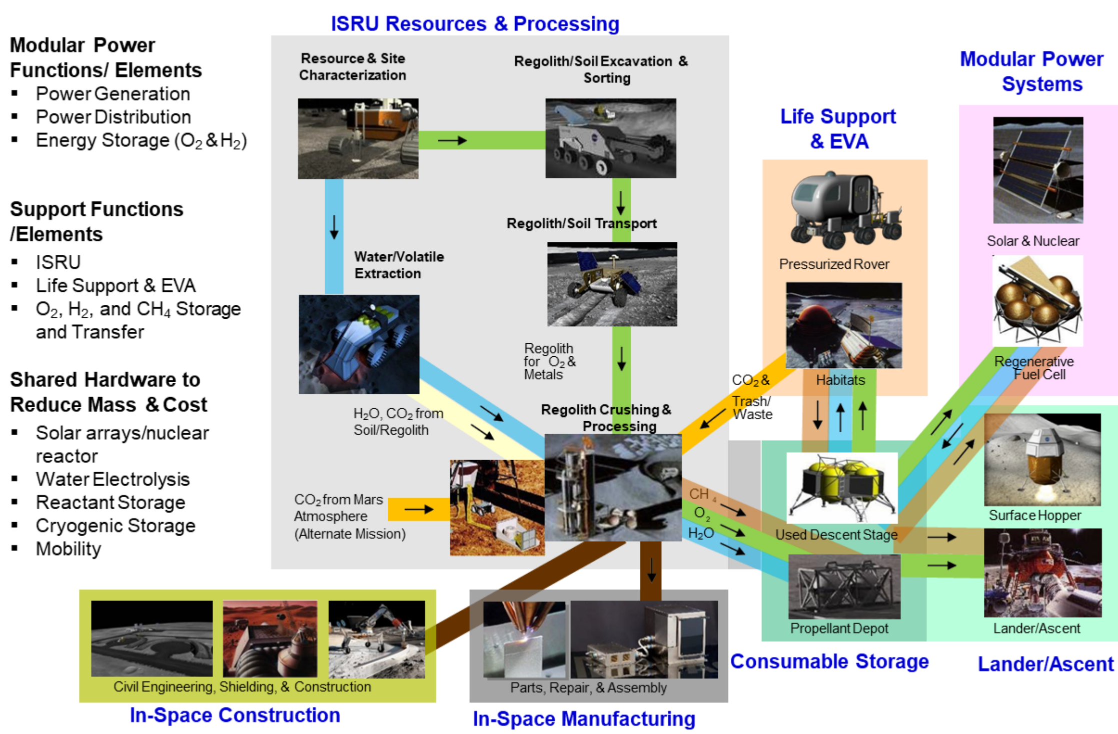


Figure 4-2: NASA Lunar ISRU SoS functionality flowchart [136]

Figure 4-2 shows several possible ‘customers’ for ISRU activities that are being considered for inclusion. Note that Figure 4-2 (circa 2019) mirrors the content from a 2007 flowchart, albeit with updated graphics, showing the influence of Constellation Program efforts upon ideas for ISRU within the Artemis Program [3], [136]. Notable differences include the addition of a 'surface hopper' for sorties, a reduced emphasis on in-situ construction like landing pads and habitats, as well as improved groupings of functions. The possibility of parallel processing for metals and volatile gases is also of interest, though volatiles are the focus of this work. When comparing the process represented by this Lunar ISRU flowchart to the ISRU processes within Mars DRA 5.0, Figure 4-2 adds prospecting to find resources of interest and transport of materials, as well as noting a dependency upon power availability. This 'shared hardware' denotes interlinked dependencies of systems indirectly related to resource processing that must also be considered.

4.1.2 Spacecraft Systems

Though one such system ISRU capabilities are dependent upon has been identified as power systems, additional required capabilities can be found by examining common spacecraft subsystems as described in *Space Mission Engineering* [137, p. 411]. Thermal control stands out as an important consideration, due to significant temperature swings involved in many processing methods. It is conceivable that a concept could involve heating rock to sublimate water as well as cooling propellants for cryogenic storage. Processes such as these require careful monitoring from onboard systems, motivating a need for avionics. These electromechanical systems could also handle telemetry, tracking, data handling, and communications.

The navigation and orientation of a spacecraft is another important set of functions, but one that does not map as nicely to ISRU. Typical systems include attitude control, orbital determination, and propulsion [137, p. 411]. Propulsion is certainly needed for the return vehicle included in the selected mission, though orbital control does not seem to be the proper term for a system that must be in contact with a NEO for an extended period of time to collect substantial quantities of material. Rather, something is needed to secure equipment in place and also move it if necessary. Some sort of responsive anchoring mechanism is needed, something more in line with moveable structures containing actuators. Thus, the means for spacecraft motion controls will be lumped together with structures due to anticipated similarities in form when attached to a NEO.

4.1.3 Implications of Mass Flows

Another unusual aspect of ISRU from a spacecraft systems perspective is the need to handle significant flows of matter in the design. These differences are emphasized in an earlier NASA roadmaps put forth on the development of ISRU capabilities, in the form of the five types of technologies put forth as areas where capabilities were lacking [2]. These areas primarily involve the processing on matter in-situ, with the notable exception of the last bullet point on the difficulty of mission assurance echoed by other authorities [98]. Redundant systems and clever control logic are possible solutions that should be considered in design concepts.

Sanders (2000): NASA ISRU Roadmap “five major technical areas” [2]

- Resource Collection and Conditioning
- Chemical Processing
- Material Processing
- Cryogenic Liquefaction and Storage
- Survivability and Autonomous Operation

Returning to the Lunar and Martian ISRU concepts discussed earlier, Figure 4-2 focuses on the useful portion of matter flows that are being processed. These space resources must be found, excavated, transported, extracted, further processed, and then stored before use. It is worth noting that the transportation of matter is handled differently in Figure 4-1, with several pumps and valves shown rather than a rover carrying regolith. These capabilities can be reconciled by noting they are both forms of material handling. Though transport is only mentioned once in Figure 4-2, the array of piping between all components in Figure 4-1 make it worth noting that material must be handled each step of the way, especially between equipment. It is recognized that each of the arrows depicting a flow of matter in Figure 4-2 must similarly have hardware built to facilitate that flow. A similar flow for NEO ISRU was proposed by Gertsch et al. [80]. This is notable for its attention to the emplacement of equipment in stages and attachment mechanisms.

Gertsch et al. (1997): Proposed NEO Mining and Processing Steps [80]

1. Anchoring to the NEO, and tether attachment
2. NEO motion control: Partial or complete de-spin and de-wobble
3. Body/fragment restraint placement
4. Operations platform placement
5. Bag placement
6. Auxiliary and support equipment placement
7. Mining operations
8. Processing operations
9. Transportation operations
10. Mitigation by orbital modification

Though most ISRU concepts consider what is to be done with the resources of interest, few consider what is to be become of the rest of the matter that is left behind after extraction or otherwise in excess of what is needed. All material being handled must have a destination in mind, especially when considering conservation of mass. Consumables produced are typically stored for retrieval. In the case of bipropellant production though, oxidizer is typically produced in excess of what is needed since most rocket engines run fuel rich to improve specific impulse and fuel demand is driving the sized capacity. In concepts that consider other matter besides the primary resource of interest, the usual cop-out is to postulate that everything can be made useful somehow; this can be seen in Figure 2-8, Figure 4-2, and Figure A-17. This of course introduces additional technologies requiring development as well as complexity into the design.

For flight missions, extra mass has historically been ejected from the spacecraft. Used rocket stages are routinely jettisoned, and resupply spacecraft departing from the ISS filled with trash burn up upon atmospheric reentry. Excess process gasses are typically vented into space, such as the methane produced by the Sabatier reactor within the Carbon Dioxide Removal Assembly on the American side of the ISS [138]. Before the Sabatier reactor was installed, captured carbon dioxide was vented into space [139]. The precedent left by rovers drilling rock samples is to sweep the kerf out of the way or leave it where it falls. This technique is not anticipated to scale well, as the relatively large quantities of rock that need to be processed to obtain meaningful quantities of resources are likely to get in the way of excavation, or exacerbate existing issues with abrasive regolith, or occlusion from dust storms and/or static cling. In the microgravity environment of a NEO space debris also becomes a concern. Additional consideration for what to do with the waste products of ISRU processes is certainly needed.

4.2 Functional Decomposition to Relevant Subsystems

By piecing together the identified functionality that is needed for NEO ISRU from the previous subsections, a picture of the systems present in the design solution is formed. This functionality can be divided into direct and indirect, based upon the degree of interaction with space resources, as seen in Figure 4-3. Functionality specific to the sample return mission rounds out the required capabilities, though is omitted from the graphic for clarity. Note that terms are typically bolded when defined in this work:

- **Direct ISRU** is the means by which a sequence of events for the processing of space resources is enacted.
- **Indirect ISRU** involves functionality that is necessary to support ISRU activities, but not meaningfully interacting with the products produced.
- **Sample Return** is a third set of functionality (not shown) which captures additional aspects of the selected mission not otherwise included, like return vehicle options.

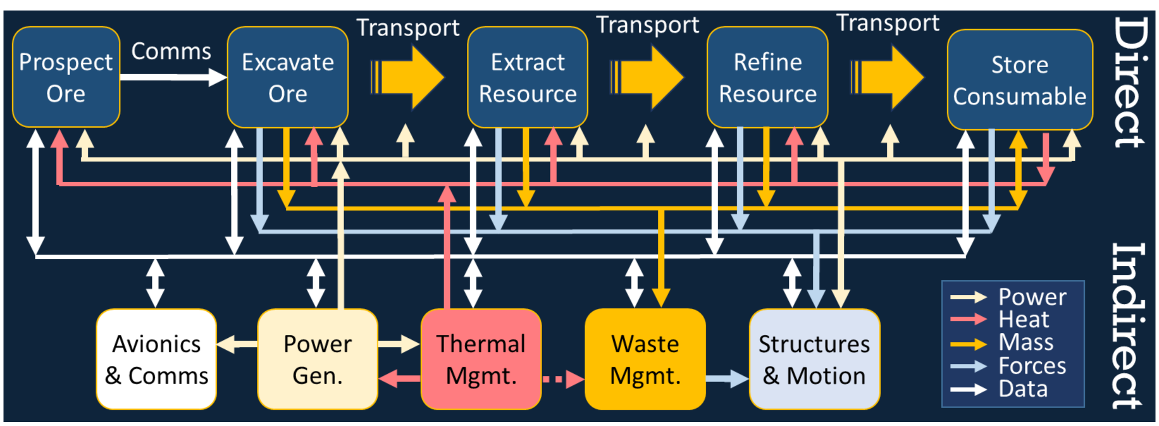


Figure 4-3: Functional decomposition of ISRU to system level, with possible interconnections between systems noted.

A number of potential connections between systems were included in Figure 4-3 to highlight the interconnectedness of such a design, as well as the fact that hardware is needed to facilitate many types of connections. Note that prospecting is unique among direct ISRU systems, as it is assumed to be in orbit of the NEO wider area coverage, while the others are assumed to be anchored to the surface of the NEO for better access to raw materials. Data links are shown with double headed arrows to represent a bidirectional flow of information between sensors, computers, and actuators in all systems. Power and thermal are anticipated to provide energy to other systems, with wastes and structures acting as sinks for demand. Storage may include return vehicle tanks, as well as others.

Also within Figure 4-3 are terms regarding matter at different stages of processing. In line with the observations about current difficulties in comparing concepts, it is prudent to establish definitions for these terms to be used in this work. In this way, more meaningful definitions for direct ISRU systems can be formulated based upon the functionality they impart at their respective stage of processing. See § 5.3.1 for relationships of terms.

- **Resources** are things or conditions with perceived value. In a processing context, an intermediate substance with ore and consumable forms is typical (e.g. water).
- **Regolith** will generally refer to bulk matter of the NEO in its natural 'rubble pile' state, with distinctions made between loose regolith and solid rock when necessary.
- **Ore** is the material containing the resource in its raw form (e.g. hydrates).
  Ore can be a small portion of regolith to all of it, depending on the uniformity of composition and how well higher grade deposits can be detected and accessed.
- **Overburden** is the component of regolith that is not considered to be ore.
  Alternatively, overburden is regolith that is excavated but not subject to extraction.
- **Volatiles** are gasses evolved from heating ore, usually during extraction.
- **Tailings** are the portion of ore that is left after volatiles have been extracted.
- **Consumables** are processed and purified resources ready to be used (e.g. oxygen).
- **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.

With these definitions in mind, functional decomposition can be continued from the systems level down to the subsystems level. Taking this step is desirable since technologies are typically injected into a design at the subsystem level as per Figure 2-6, enabling candidate technologies with similar functionality to be categorized together to aid comparisons. By conducting a sufficiently wide-ranging literature review, a close to functionally complete list of categories can be created. Note that though every effort has been made to make the resulting list comprehensive for the selected mission under consideration, it is entirely possible that a function was overlooked like in prior efforts.

Since similar terminology with differing meanings is used in various sources, this work attempts to provide both definitions and context to aid understanding. Note that some ideas may be at different design levels than used historically (e.g. beneficiation as a subsystem of extraction) due to the more holistic yet mission specific nature of this work, as well as the rather inclusive definitions used. Also note that the functionality of each subsystem can be further subdivided, though more general categories are preferable here to permit comparisons between fairly dissimilar design solutions.

Instead of defining the identified systems in Figure 4-3 as a group, they are each unpacked individually in the following subsections. The system of interest is described, along with areas relevant research in the field. A set of relevant functionality is then discerned by summarizing the concepts at hand. Particularly of interest here is the Capability Breakdown Structure (CBS) on ISRU prepared by NASA in 2005, with the top three levels depicted in Figure 4-4 [4]. Many capabilities described are not applicable to the selected work or beyond the scope (e.g. ground testing), though this has the benefit of introducing ideas that might be otherwise overlooked.

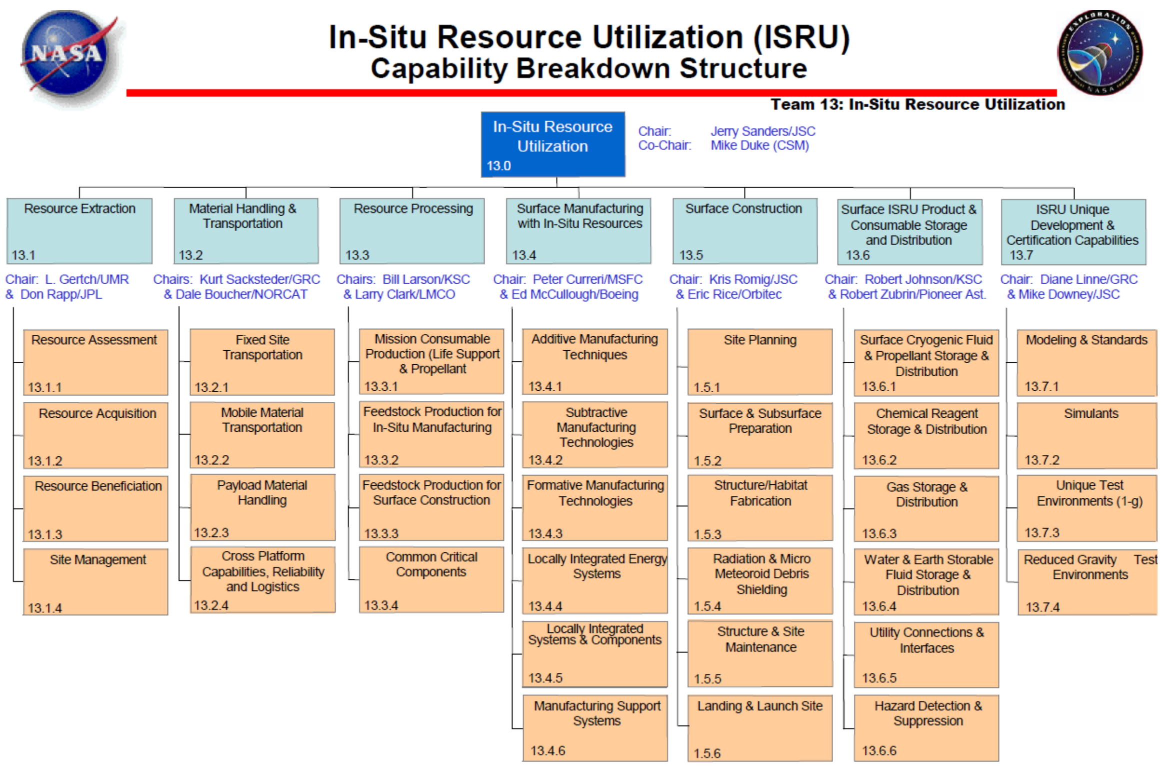


Figure 4-4: 2005 NASA ISRU Capability Breakdown Structure, levels 2 and 3 [4]

4.2.1 Direct ISRU

Many groups of capabilities identified in Figure 4-4 can be linked to the sequence of events directly involved with the processing of space resources shown in Figure 4-3 [4]. Prospecting for ore deposits is analogous to NASA CBS 13.1.1: ‘Resource Assessment’. Extracting ore from the parent body is analogous to 13.1.2: ‘Resource Acquisition’ and 13.1.3: ‘Resource Beneficiation’, though restricted in scope to solid rock and/or loose regolith. Extraction of volatiles from ore is not considered independently in the NASA CBS, though assumed to be part of 13.1.2: ‘Resource Acquisition’. Refining the volatiles into consumables is analogous to 13.3: ‘Resource Processing’. Storage of consumables is analogous to 13.6: ‘Surface ISRU Product & Consumable Storage and Distribution’. Transportation of matter between equipment, or material handling, is analogous to 13.2: ‘Material Handling & Transportation’. In this light, these systems are defined as follows:

- **Prospecting** is the discernment of locations with greater concentrations of space resources on or within the target NEO that are reasonably accessible.
- **Excavation** is the process of separating the ore from the NEO, or otherwise directly interacting with the NEO to release resources.
- **Extraction** refers to the removal and purification of resources of interest from ore.
- **Refining** is defined here as the processing of resources from an intermediate state into a readily useable form termed a consumable.
- **Storage** refers to methods for preservation of consumables for future use.
- **Material Handling** examines methods to transport mass between locations [140].

There have been a variety of development efforts over the years to develop direct ISRU systems for ISPP, albeit by different names. The most notable of these are associated with NASA crewed exploration efforts, such as the Martian methalox plant flow chart shown in Figure 4-5 from 2018 [141]. This flow chart is of particular interest since it shows example excavation, extraction, refining, and storage options for methalox production that can be generaized into functions to be satisfied in this subsystem functional decomposition.

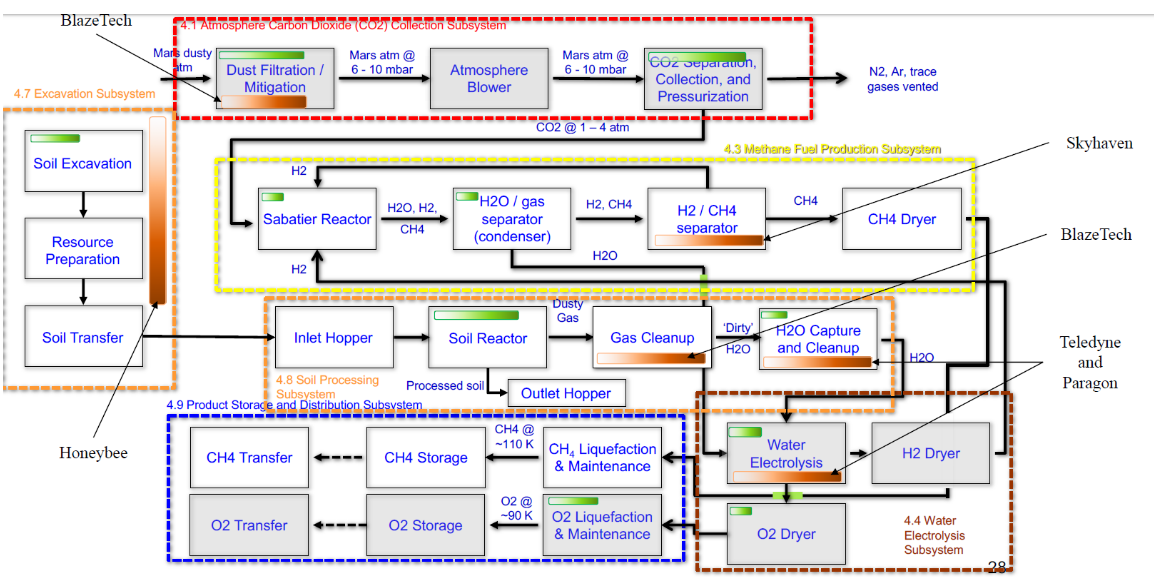


Figure 4-5: NASA "Mars Traditional Water Electrolysis Option" for a methalox ISPP SoS, showing proposed subsystems and contractor development status [141]

4.2.1.1 Prospecting

The first step in utilizing space resources is to identify recoverable deposits of them. To these ends, prospecting is the discernment of locations with greater concentrations of space resources on or within the target NEO. This is a special case of direct ISRU since the prospecting system does not necessarily need to be in direct contact with space resources, though it is required to give directions on where to excavate. Note that the prospecting system is restricted here to NEO proximity operations, as sensors to find ice within a NEO would likely be flown with an ISPP plant, through telescopes to find which NEO has more ice would likely be beyond the scope of the selected mission as a separate mission in their own right. Precursor missions (esp. sampling) are also beyond the scope, unless they leave hardware which is used again after other ISRU systems arrive.

It is worth noting that companies have tended to put an outsize emphasis on identifying space resources, since a belief has emerged that better data on space resource availability is required to gain enough investor confidence in their business model to proceed with private development efforts [103], [142], [143]. Of these companies, Deep Space Industries focused on building a better business case to identify deposits from available data, while TransAstra Corp. worked on optical telescopes. Planetary Resources got the farthest by designing a kinetic penetrator for sampling, and flying a prototype near-infrared camera on a CubeSat in 2018 [142]. On the public side, there have been five sampling missions to date of NEO that could be counted as precursor missions to identify space resources, or used as a model for prospecting techniques. Two have been to comets (NASA Stardust and ESA Philae), and three to different asteroids (JAXA Hayabusa, JAXA Hayabusa 2, and NASA OSIRIS-REx) [79], [118]–[121].

From these public and private actors, a few thoughts can be had on required high-level functionality of a prospecting system operating in the vicinity of a NEO. Although a well-designed prospecting system tends to have multiple types of instrument packages involved in local observation to corroborate data, only the primary instruments are explicitly considered here to simplify the number of categories considered within the morphological matrix. Prospecting efforts in the vicinity of NEO can be understood as either remote sensing and/or sampling of matter. Remote sensing can be subdivided into a means for local observation and the wave type (not necessarily electromagnetic) used to conduct those observations to increase the options considered. Identified options for the categories defined below can be found in § B.2.1.

- **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.

4.2.1.2 Excavation

After material space resources are identified, they must be isolated in some way to enable recovery. For ISPP this entails mechanically separating higher-grade ore from lower-grade overburden in the bulk NEO. Thus, excavation describes mechanical means for separation in this work. Sonter captures most of the functions of interest here, though they are grouped into different stages of the process and different terminology is used [99]. The process described involves cutting off chunks of rock in some form, comminution via grinding it down in size, then sorting the resulting fine particles. Of the existing concepts examined, excavation tended to be more of a focus when the resource of interest was metals or bulk rock. Particularly notable design examples include the boring head developed by the University of Washington, the bucket wheel from Arizona State Bucket Wheel, and the 'Rock-Breaker' from Georgia Tech [144]–[146]. Also of note is that concepts that consolidated excavation and extraction systems like the TransAstra Honey Bee and the HoneyBee Robotics Spider tended to de-emphasize particle size in processing or attempted to make their processes particle size agnostic [89], [147].

From these observations, the two main aspects of excavation include: liberating ore from the NEO in a controlled fashion, and particle sizing. Liberating ore can be described as cutting into the rock, and containing both debris and ore recovered. Particle sizing can be described as efforts to reduce particle size and means to mechanically sort the resulting particles. These categories are defined below, with identified options in § B.2.2.

- **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.

4.2.1.3 Extraction

After space resources are physically isolated, they can be concentrated and purified. For ISPP, this entails taking ore and removing its volatiles, then separating the volatiles by chemical species. The evolution of volatiles through sublimation requires heating in some form, though capturing these released volatiles may involve more than cooling them back down [99]. Thus, the functions of primary heating and volatile capture are identified for inclusion within the extraction system. Primary is used to distinguish heating functionality in extraction from thermal management, with a greater heating demand expected here. Two main types of extraction systems noted in existing concepts for propellant production were sublimation and spalling based systems. Sublimation based extraction focuses on heating ore to evolve volatiles, as exemplified by the resistance heaters in the walls of HoneyBee Robotics' Planetary Volatiles Extractor (PVEx) corer [148]. Spalling based extraction focuses on the ablation of ore from intense light or jets, as exemplified by TransAstra's Honey Bee concept and the 'optical mining' technique under development [89], [149]. These spalling systems tend to have some form of beam transmission involved.

- **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.

Note that several sources (including the examples above) do not distinguish between excavation and extraction, instead using one term to refer to both or another term such as 'Resource Acquisition' in the NASA CBS [4]. A distinction is made in this work to point out the different roles of the functions involved, and to highlight the increasing specificity of operations in the sequence of excavation to extraction to refining. In this vein, beneficiation to increase the concentration of resource(s) under extraction is presented as analogous to powderization to increase surface area under excavation. This is a more specific role for beneficiation than has been used historically in the literature, but is felt to be appropriate due to the definition of extraction used in this work including purification of resources [4], [99]. Beneficiation also serves to separate out evolved impurities like sulfur compounds, important functionality that was only present in one existing concept: Pioneer Astronautics' Carbonaceous Volatile Asteroid Recovery (CAVoR) [38], [91]. Thus, the three main functions of extraction have been identified, with options in § B.2.3.

4.2.1.4 Refining

After resource intermediates are sufficiently purified, these resources can be processed into consumables. For ISPP, this entails reactions between chemical species to produce propellants. Since the selected mission focuses on producing propellant, metal processing and fabrication methods are not considered. Note that the extent of capabilities required within the refining group depends heavily on which propellant is selected to be produced by the SoS NEO ISPP. In addition, beneficiation is placed under extraction and assumed a prerequisite for refining, due to the definition of extraction used in this work and the markedly low impurity tolerances of acidic electrolyzers such as those currently used in the ISS Oxygen Generation System [150]. This is by design, concentrating changes between morphological options within the refining system and the return vehicle when different propellant types are selected, in order to better discern how the sizing of other systems changes.

To decompose the refining system, the most chemically complex propellant considered is used to dictate the functionality required. Figure 4-5 is of particular interest for examining refining functions required to create methalox propellant [141]. Pioneer Astronautics' Carbonaceous Volatile Asteroid Recovery (CAVoR) and TransAstra's

Fontus are both examples of NEO refining systems producing methalox from the literature [11], [38]. All three propose some form of electrolysis to split water into hydrogen and oxygen, though means to produce methane differ. Since some ISRU proposals involve only producing oxidizer from metal oxides and/or bringing hydrogen, oxygen production is considered a separate function from hydrogen production [30], [129]. This gives three functions: make oxygen, make hydrogen, and make methane. A source for the carbon atoms in the methane product is also needed, with hydrocarbons of some form noted to exist in primitive asteroids as a probable source [50], [151]. Though heat from extraction can be used to decompose compounds, other options involve chemical reactions, thus cracking of hydrocarbons is felt to be best addressed within the refining system. Another important function that is often overlooked is process monitoring (2nd most common as per Table 7-1), as represented by NASA CBS 13.1.4.6 [4]. This function can be generalized to quality control to admit additional alternatives. Identified options for the categories defined below can be found in § B.2.4, with different options referring to alternative reactions or methods to provide energy for said reactions to occur. Note that a variety of intermediate steps like additional separation tasks are implied but not explicitly included here, in order to simplify the number of categories under consideration.

- **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.

4.2.1.5 Storage

After the consumables are produced, they are preserved awaiting use. Even if there is minimal delays between completing propellant production and departure of the return vehicle, propellant produced earlier in the process is accumulated over time. Note that storage here refers to only the demanded quantity of propellant and mass of samples, as wastes produced are not necessarily stored. Note that storage and waste management can be considered in tandem if the decision is made to store waste products (see § 5.2.6).

Though there are many types of vessels and conveyance systems to store items, it can be noted that design decisions are heavily driven by the form in which the matter is stored. Differing means proposed to store hydrogen is a good example of this, with the medium chosen driving pre-processing requirements like cooling and pressurization, as well as tank wall construction and/or the presence of filler material. Efforts are also desired to minimize losses of propellant over time in storage, with minimizing boil-off of cryogenic liquids being an example such. Means to accomplish this can be active cooling, as well as passive construction like insulation or less permeable tank liners. It was decided to relegate active functionality to the thermal management system due to anticipated similarities, leaving insulation functionality in the storage system. Note that multiple insulation methods are typically used together, though only the main one is included for simplicity. Identified options for the categories defined below can be found in § B.2.5.

- **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.

4.2.1.6 Material Handling

Throughout the processing of space resources, matter must be transported between and within ISRU systems. Though each of these connections could be considered a design choice in its own right, similarities in form of design solutions for like functions are assumed in this work to reduce the complexity of the resulting functional condition. From this perspective, the primary considerations are the state of matter, and how energy will be input to do work upon the system. Two types of matter flows are considered in this work: granular solids, and fluids.

- **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 [152].
- **Work Input** is the primary method of providing energy for material handling.

Aspects of material handling are included under NASA CBS 13.2: 'Material Handling & Transportation' as well as 13.6: 'Surface ISRU Product & Consumable Storage and Distribution' [4]. Granular solid transport techniques worthy of note are the augers within Star Technology & Research's Cornucopia, and the pneumatics developed for HoneyBee Robotics' PlanetVac [153], [154]. Fluid transport generally involves pressure gradients. Identified options for the categories defined above can be found in § B.2.6.

4.2.2 Indirect ISRU

With the decomposition of systems directly involved with the processing of space resources, the next step is to better describe systems that are indirectly involved in the supporting roles shown in Figure 4-3. A key feature of the SoS approach taken in this work is that other disciplines in supporting roles are considered in tandem, to better understand interactions with direct ISRU capabilities. After all, processing matter flows requires significant energy flows to be harnessed and directed as needed. The selection and sizing of systems to accomplish this varies considerably with the magnitude of different forms of energy demanded by direct ISRU systems, as well as the properties of the NEO destination selected. For example, differing extraction heating methods and the varying limits upon heliocentric distance in non-circular orbits are both thought to significantly affect the choices for indirect ISRU subsystems, meriting further examination of options.

Though aspects of indirect ISRU systems can be found in the 2005 NASA CBS of which Figure 4-4 is a part, probes sent out into deep space serve as a better analogy for required capabilities. Avionics considers aspects of data handling, in how commands are processed and means for communication. Power management describes means to harness electrical energy. Thermal management keeps equipment in a safe temperature range by both heating and cooling as appropriate. Waste management describes where to put processed matter besides the demanded quantity of consumables after other systems are done with it. Structures describes mechanisms to bear loads and control attachment to the NEO, especially anchoring the craft. Connections between systems are considered part of the parent indirect ISRU system (e.g. coolant loops are within thermal management) as deemed appropriate. Definitions for these systems are formalized here:

- **Avionics** or data system refers to the command, control, and communication aspects of coordinating a SoS. Note that effectors are not included here.
- **Power** management refers to the primary means by which electrical energy is harnessed throughout the SoS.

- **Thermal** management refers to active methods by which the thermal energy of systems within the SoS is kept within permissible limits.
- **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).
- **Structures** refers to equipment designed to bear mechanical loads and maintain control of the spacecraft (esp. anchoring to the NEO).

4.2.2.1 Avionics

The first of these indirect ISRU systems to be examined is the network of computers that coordinates the operations of the other systems. Aspects of avionics considered here are included in NASA CBS 5.0: 'Communication & Navigation', and 10.0: 'Autonomous Systems and Robotics' [4]. The avionics hardware and its corresponding software can also be termed the data handling system, with an eye towards command, control, and communications. Note that the effectors for enacting changes to maintain control are outside the scope of this system, with coolant loops and anchoring mechanisms being notable examples. What is included in avionics is a rough estimate of the quantity of computer processor units required, and means for communicating data. Key decisions about the computer hardware include the degree of onboard data handling and decision making represented by autonomy, and the distribution of computer nodes within the SoS as described by computation. As for communications, those both near and far must be accounted for. Identified options for these categories can be found in § B.3.1.

- **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.

4.2.2.2 Power Management

Of course, avionics require electricity to run, much like many other systems within a spacecraft. Aspects of power management are included under NASA CBS 2.0: 'High-Energy Power and Propulsion' [4]. Note that power management is restricted in scope to providing electrical energy used to power other systems in this work. Electrical signals are part of avionics, thermal energy is in thermal management, and kinetic energy is elsewhere.

This narrow scope is intentional, to make variations in electrical demand upon sizing more discernable at the system level. This demand is satisfied by generating electrical power, and storing energy to smooth out demand and supply. This is especially important when using solar panels to account for light/dark diurnal cycles, though energy storage was the most neglected function identified (Table 7-1). Having a category for electrical transmission (e.g. alternating vs. direct current) and/or bus voltage was considered, though it was felt these topics provided more detail than required for pre-conceptual design decisions. Identified options for the categories defined below can be found in § B.3.2.

- **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.

4.2.2.3 Thermal Management

Another important yet overlooked system is the control of heat and temperature. ISRU fundamentally involves using energy to transform space resources into useful forms, these transformations tend to require changes in thermal energy or produce waste heat. Select aspects of thermal management are included under NASA CBS 13.6.5.1: 'Thermal Management' as well as 2.0: 'High-Energy Power and Propulsion' [4]. Note that three of the five thermal functions identified here are in the top five most commonly overlooked functions, missing in at least 70% of existing NEO ISRU concepts examined (Table 7-1).

Thermal management needs to involve both heating and cooling equipment, as extraction of volatiles involves high temperatures though subsequent processes require lower temperatures. Equipment is also expected to be subjected to temperature swings from diurnal cycles from NEO rotation, unless a particularly small NEO is selected. The heating functionality within the thermal management system aims to keep electronics and mechanical components warm enough to operate. This is designated secondary heating, since primary heating is anticipated to be higher-power with specialized requirements.

Means of transferring heat throughout the SoS are also needed. Heat transfer through convection is facilitated by distribution channels, with radiation facilitated by focusing beams of electromagnetic waves. These distribution channels can be coolant loops, through regardless of form heat exchangers of some kind are needed to transfer heat to/from them. Beam transmission involves directing electromagnetic waves such as through the use of solar concentrators or fiber optics fed by a maser. Identified options for the categories defined below can be found in § B.3.3.

- **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 (esp. coolant loops).
- **Beam Transmission** refers to methods to transfer electromagnetic waves throughout the SoS (esp. for cutting beam).

4.2.2.4 Waste Management

As a result of direct ISRU processes concentrating desired resources, various waste products with depleted levels of the resource will necessarily result. Select aspects of waste management are included under NASA CBS 13.1.4.8: 'Waste Management' [4]. Several optimistic thinkers postulate that a use can be found for everything extracted, though the author notes that this would increase development costs and introduce an unnecessary amount of complexity for a pilot system focused on propellant production. In addition, techniques that leave bulk NEO in place for extraction are viewed with scepticism, due to the lack of a good gas seal permitting evolved volatiles to escape through porous rock or between pebbles in the rubble pile of the NEO bulk, thus drastically decreasing yields. Thus something must be done with these wastes, though several options exist.

As discussed previously, wastes are anticipated to come in four forms: overburden of low-grade rock, tailings after volatiles have been extracted, byproducts from refining, and excess consumables produced. It can be noted that overburden and tailings are both granular solids (aka powders), while byproducts and excess are both fluids. By considering these like forms together, matters can be simplified for pre-conceptual design. Note that four distinct categories (overburden, tailings, byproducts, & excess) would likely be used further on in the project lifecycle. Note that dealing with granular solid wastes was tied for the fourth most neglected function identified in exiting concepts (Table 7-1). Identified options for the categories defined below can be found in § B.3.4.

- **Tailings & Overburden** comprise the end state for unwanted powders produced.
- **Byproducts & Excess** comprise the end state of unwanted fluids produced.

4.2.2.5 Structures

Last but not least of the indirect ISRU systems is equipment designed to arrest relative motion and latch onto the target NEO. Structures and mechanisms to bear loads and control attachment to the NEO are considered in NASA CBS 13.1.4 'Site Management', though some of 3.0: 'In-Space Transportation' and 10.0: 'Autonomous Systems and Robotics' also applies [4].

Structures is broadly interpreted here to include both fixed mechanical load paths and mechanisms to interact with the NEO with capabilities beyond excavation. Functionality to anchoring the spacecraft to the NEO can be considered analogous to the telemetry, orbital determination, and altitude control capabilities of free-flying satellites. This need for an anchoring system for NEO operations is fairly unique for a space system, as most spacecraft are operated far from other spacecraft the majority of the time (rendezvous excepted), and most landers operate within a significant enough gravity well to provide a restoring force holding them in place. De-spin or de-wobble is also considered here, as methods to reduce the rotational energy of the NEO could reduce the forces experienced by anchoring structures and make it easier to touch down on the NEO in the first place [80]. An underlying support structure is required as well to transfer mechanical loads. Identified options for the categories defined below can be found in § B.3.5.

- **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.

4.2.3 Sample Return

Though the vast majority of required functionality for the selected mission is captured by the direct and indirect ISRU systems already described, there are a few additional aspects to discuss. Sample return focuses on customer mission assurance for ISRU, attempting to capture necessary details about the mission that might otherwise slip through the cracks. Characteristics of the return vehicle are included here, especially information on its propulsion system. Select systems engineering concerns on mission assurance are addressed by integration. Definitions for these terms are formalized below.

- **Integration** is used here to refer to the modularity and adaptability of the SoS.
- **Return Vehicle** refers to a spacecraft that is designed to transport NEO regolith samples from the NEO back to Low Earth Orbit (LEO).

4.2.3.1 Integration

High level mission assurance is interpreted here to consist of the ability of the system to work though failure modes. Aspects of integration are included under NASA CBS 15.0:

‘Systems Engineering Cost/Risk Analysis’ [4]. To avoid the complexities of maintenance robotics and crewed servicing, only the degree of redundancy included and how orbital replacement units are structured are considered in the ability of the concept to adapt to failures. Options for redundancy are largely taken from *New SMAD* [137]. Separation considers how modular and/or disaggregated the concept should be during operations. To simplify matters, the level of separation & redundancy selected are assumed to be fully consistent across all systems in the SoS for modeling purposes. Identified options for the categories defined below can be found in § B.1.1.

- **Separation** refers to physical detachment permitted between systems within a SoS.
- **Redundancy** refers to how the risk of subsystem failure is mitigated in the design.

4.2.3.2 Return Vehicle

The customer for ISPP is ultimately the spacecraft that will use the propellant produced, especially its propulsion system characteristics. In the selected mission of sample return, this spacecraft is termed the return vehicle and is intended to transport samples from the NEO back to Low Earth Orbit (LEO). Aspects of the return vehicle propulsion are included under NASA CBS 3.0: ‘In-Space Transportation’ and 2.0: ‘High-Energy Power and Propulsion’ [4]. To these ends, several existing concepts from the literature have NEO return vehicle concepts worthy of note. TransAstra’s Honey Bee (Figure A-1) utilizes solar thermal propulsion to return the whole craft [89]. Surculus Astrum includes a nuclear electric tug (Figure A-11), with argon anticipated as propellant on the way out, switching over to water on the way back [144]. The series of spherical propellant tanks behind a sunshade supplying a single chemical rocket engine (Figure A-9) from *Delta-v* is also of interest [155].

Though a plethora functionality is required to operate a return vehicle, it is outside the ISPP plant boundary and thus only high level functionality impacting ISPP will be considered here. Chief among these is the selection of the propellant to be used, and the form of propulsion used to expel it as reaction mass. Note that mass drivers are specifically excluded due to space debris concerns. Only propellants that can be produced from NEO resources are considered. For chemical propellants like hydrolox the stoichiometry of combustion is an important consideration, as the commonly used fuel rich mixture ratios that increase specific impulse also lead to substantial excess oxidizer being produced.

When it comes to the return type specified, there is an intrinsic trade off here between expending systems for higher performance, and holding on to systems to facilitate easier reuse. This is captured by the return type function, which describes how much of the concept returns with the sample to LEO versus being left behind at the NEO. The inclusion of differing trajectory types such as options for a lunar gravity assist or aerocapture were also considered, though it was ultimately decided to assume propulsive capture in LEO to simplify the analysis. Such a distinction in trajectories would have likely necessitated computing return Δv values for each option, instead of using those from the literature. Identified options for the categories defined below can be found in § B.1.2.

- **Propulsion** refers to the principal method used to accelerate the return vehicle by providing thrust.
- **Propellant** refers to the choice of which substance is ejected at high velocity from the spacecraft to provide thrust.
- **Chamber Reaction** refers to the stoichiometry of the rocket engine reaction.
- **Return Type** describes how much of the SoS NEO ISPP is returned to LEO

4.3 Morphological Matrices

With the functional decomposition completed down to the subsystem level, the next logical step is to start seeking options to provide those functions, as well as an organizational scheme to structure the options that turn up. Morphological matrices were introduced in § 3.2.1 as a good way to accomplish this. In this case, the structure is provided by each decomposed subsystem becoming a row that can be populated to create a category of morphological options.

4.3.1 Existing NEO Concepts

A natural starting point to begin populating this morphological matrix is to return to the concepts which helped aid the functional decomposition. By noting what each concept did or did not do to satisfy a functional niche, significant headway can be made. A breakdown of each of the eighteen NEO ISRU concepts for each category in the morphological matrix is shown in Table 4-2. There appears to be a somewhat cyclic interest in NEO ISRU concepts as shown in Figure 4-6 with data taken from Table 4-4, though

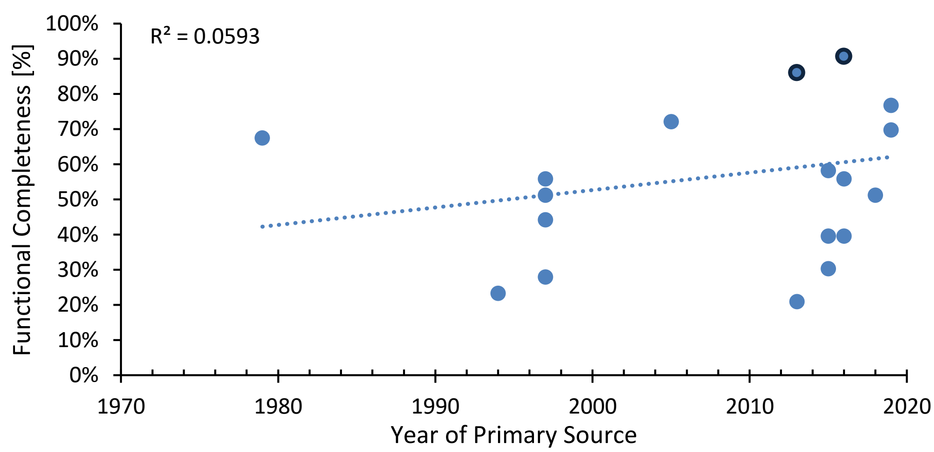


Figure 4-6: Assessed functional completeness of existing concepts, as compaired to publication year of the primary source on that concept. Duplicate points are circled.

Table 4-2: Existing NEO concepts characterized by morphological options (part 1 / 3)

20 Options Identified
v.5.1 7/15/2020

Key to Options: Option for Case Study | Null Option (not needed) | Violates Mission Assumpt. | Unspecified in Literature

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)
Sample Return	Integration	Separation	Single Unit (None)	Single Unit (None)	Single Unit (None)	Detachable Modules	Swarming Craft	Swarming Craft	Swarming Craft
		Redunancy	Independent Strings	Independent Strings	Independent Strings	Independent Strings	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)
		Propellant	Water/Steam	Water/Steam	Water/Steam	Noble Gas - Xenon	N/A	Noble Gas - Argon	Methalox
		Chamber Reaction	N/A	N/A	N/A	N/A	N/A	N/A	? (Unspecified)
		Return Type	Partial / Some Systems	Whole SoS	Whole SoS	Return Vehicles	Return Vehicles	N/A	Return Vehicles
Direct ISRU	Prospecting	Local Observations	Precursor, Passive Observati	Sampling Only	Precursor, Sampling Only	Passive Observation	Active Observation	Active Observation	Active Observation
		Wave Type	Visible Light	N/A	N/A	Visible Light	Visible Light	Radar	Visible Light, Subatomic Part
		Sampling	N/A	Excavate (automated)	Kinetic Penetrator (smart)	N/A	N/A	? (Unspecified)	N/A
	Excavation	Containment	Synched Bag	Tube Sleeve	Clamshell Enclosure	Tube Sleeve	Localized Membrane	N/A	Synched Bag
		Cut Rock	Optical Beam (spalling)	Auger Bit	Optical Beam (spalling)	Auger Bit	Optical Beam (spalling)	Beam (laser) & Jet (plasma)	Rotary Cutter
		Powderize	N/A	Cut Debris (Kerf/Spall)	Cut Debris (kerf/spall)	N/A	N/A	Cut Debris (kerf/spall)	Rip/Fracture
		Sorting/Sizing	N/A	N/A	N/A	N/A	N/A	N/A	Centerfugal & Filtration
	Extraction	Heating [Primary]	Focused Sunlight	Resistance (electrical)	Focused Sunlight	N/A	Laser (artificial)	Jet (plasma)	Focused Sunlight
		Beneficiation	N/A	N/A	N/A	N/A	N/A	Fabry-Perot Resonator	Centerfugal & Chemical
		Volatile Capture	Cold Trap (condensation)	Cold Trap (condensation)	Cold Trap (condensation)	N/A	Cold Trap (condensation)	N/A	Condenser
	Refining	Make Oxygen	N/A	N/A	N/A	N/A	N/A	N/A	Split Water
		Make Hydrogen	N/A	N/A	N/A	N/A	N/A	N/A	Electrolysis (Unspecified)
		Crack Hydrocarbons	N/A	N/A	N/A	N/A	N/A	N/A	Pyrolysis (Heat)
		Make Methane	N/A	N/A	N/A	N/A	N/A	N/A	? (Unspecified)
		Quality Control	? (Unspecified)	Process Monitoring	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Storage	Medium	Cryogenic Solid (Ice)	Liquid (Water)	Liquid (Water)	Solid (Regolith)	Cryogenic Solid (Ice)	Solid (Regolith)	Liquid & Granular Soilds
		Insulation	Sunshield / Shade	Multi-Layer Insulation (Exter	? (Unspecified)	? (Unspecified)	Multi-Layer Insulation (Exter	? (Unspecified)	Sunshield / Shade
	Material Handling	Granular Solids	N/A	Auger / Screw Feeder	N/A	Auger / Screw Feeder	N/A	Mechanical Pusher	? (Unspecified)
		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)
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Blower, A	Heating (Volume Increase)	Shaft Work (Pump, Blower, A	Heating (Volume Increase)	? (Unspecified)	? (Unspecified)
Indirect ISRU	Avionics	Autonomy	? (Unspecified)	? (Unspecified)	Autonomous (if possible)	Autonomous	Autonomous	? (Unspecified)	Automated, Astronauts on Sit
		Computation	Distributed (control boards)	Centralized	Distributed (in ORUs)	Distributed (main & systems	Distributed	? (Unspecified)	Centralized (server rack)
		Local Comms	Wired	Wired	Transmitted	Transmitted	Transmitted	Transmitted	Transmitted
		Deep Space Comms	Laser Link	Radio	Radio (steerable antennae)	Radio (Dish)	? (Unspecified)	Radio (Rectenna/Dish)	? (Unspecified)
	Power	Electrical Generation	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Photovoltaic Cells	Concentrated Solar	Photovoltaic Cells
		Energy Storage	Batteries	Batteries	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Thermal	Heating [Secondary]	? (Unspecified)	Resistance (electrical)	Resistance (electrical)	Resistance (electrical)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Cooling	Radiators	? (Unspecified)	Radiators	? (Unspecified)	? (Unspecified)	Passive	? (Unspecified)
		Heat Exchangers	Cold Plate	Finned	? (Unspecified)	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)
		Distribution	Water Loop	Peltier Effect (electrical)	Loop - (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Beam Transmission	Mirrors	N/A	Mirrors	N/A	? (Unspecified)	Beamed Microwaves	Mirrors
	Wastes	Tailings & Overburden	Secure in Place	Eject into Space	? (Unspecified)	N/A	? (Unspecified)	Storage/Reuse	? (Unspecified)
		Byproducts & Excess	? (Unspecified)	? (Unspecified)	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)	Storage/Reuse
	Structures	Support Structure	Inflatable	Truss & Recessed Lattice	Space Frame	Central Bus / Cylindrical	? (Unspecified)	? (Unspecified)	Truss, with collapsible eleme
		Positioning	Anchor / Harpoon	Friction with Excavator	Inflatable Airbags	Anchor / Harpoon	RCS Thrusters	RCS Thrusters	RCS Thrusters
		Relative Motion	Robotic Joints	Robotic Joints	RCS Thrusters	Robotic Joints	RCS Thrusters	RCS Thrusters	RCS Thrusters
		Rotation Control	Friction with Containment	? (Unspecified)	N/A	? (Unspecified)	Selective Ablation	Selective Ablation	N/A
		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
		(and title)	Asteroid Provided In-situ Sup	The World is Not Enough (Wl	Robotic Asteroid Prospector	Robotic Mining System for Ra	A techno-economic analysis	Conceptual Design of a Multi	Delta-v

Table 4-2: Existing NEO concepts characterized by morphological options (part 2 / 3)

20 Options Identified
v.5.1 7/15/2020

Key to Options: Option for Case Study | Null Option (not needed) | Violates Mission Assumpt. | Unspecified in Literature

Task	Group	Category	O'Leary et al. (NASA Ames)	Surculus Astrum (Univ. of Washington)	Kuck 'Mosquito'	Planetary Resources	CAVoR (Pioneer Astronautics)	Sonter 'Best Near Term' (Asteroid Mining Group)	Gertsch et al. 'Noncohesive Friable Rock'
Sample Return	Integration	Separation	? (Unspecified)	Detachable Modules	Swarming Craft	Subsequent Missions	Single Unit (None)	? (Unspecified)	? (Unspecified)
		Redunancy	Multiple Craft	Multiple Craft	Multiple Craft	Multiple Craft	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Return Vehicle	Thrust Class	Mass Driver	Electromagnetic (ELF)	Chemical Reaction (liquid)	Chemical Reaction (liquid)	Chemical Reaction (liquid)	Solar Thermal	Solar Thermal
		Propellant	Hydrolox (backup)	Water or Noble Gas (Argon)	Hydrolox	Hydrolox	Methalox	Water/Steam	Water/Steam & other volatile
		Chamber Reaction	N/A	N/A	? (Unspecified)	? (Unspecified)	Fuel Rich	N/A	N/A
		Return Type	Return Vehicles	Return Vehicles	Whole SoS	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
Direct ISRU	Prospecting	Local Observations	Precursor Mission(s)	Active Observation	Passive Observation	Passive Observation	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Wave Type	? (Unspecified)	Visible Light, Gamma Rays	Visible Light	Visible Light	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Sampling	? (Unspecified)	N/A	Excavate, Solar Wind	Kinetic Penetrator (smart)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Excavation	Containment	Synched Bag	Tube Sleeve	Tube Sleeve	Synched Bag	Tube Sleeve & Alumina Felt	Tube Sleeve	Clamshell Enclosure
		Cut Rock	Rotary Cutter	Rotary Cutter	Percussive Drill & Jet (Steam	Optical Beam (spalling)	? (Unspecified)	Percussive Drill & Jet (steam	Jet (water)
		Powderize	Crush (rollers, rocking jaw)	Rip/Fracture	Borehole Heating	? (Unspecified)	? (Unspecified)	Crush (Grind then Pistion)	Explosives
		Sorting/Sizing	Centrifugal (cyclonic sep.)	? (Unspecified)	N/A	Centrifugal (density)	? (Unspecified)	Sieves	Centrifugal & Tether Snap
	Extraction	Heating [Primary]	Focused Sunlight	Dielectric (artifcial)	Jet (Steam)	Focused Sunlight	Resistance (electrical)	Jet (Steam)	Focused Sunlight
		Beneficiation	Magnetic Separation	Electrostatic Sorting	? (Unspecified)	Centrifugal (density)	Reformer (inject steam & O_2)	? (Unspecified)	? (Unspecified)
		Volatile Capture	Condensers	? (Unspecified)	Condenser	Condenser	Condenser & Sorbents	Condenser	Condenser (fractional distill
	Refining	Make Oxygen	Split Water	? (Unspecified)	? (Unspecified)	Split Water	Split Water	N/A	? (Unspecified)
		Make Hydrogen	Electrolysis (Unspecified)	? (Unspecified)	? (Unspecified)	Electrolysis (Unspecified)	Electrolysis (Voltage - ?Acidi	N/A	? (Unspecified)
		Crack Hydrocarbons	Pyrolysis (Heat)	? (Unspecified)	N/A	N/A	Steam Reforming & Oxygen	N/A	Pyrolysis (Heat)
		Make Methane	N/A	N/A	N/A	N/A	Sabatier Process	N/A	? (Unspecified)
		Quality Control	? (Unspecified)	? (Unspecified)	Process Monitoring	? (Unspecified)	Process Monitoring	? (Unspecified)	? (Unspecified)
	Storage	Medium	Gas & Cryogenic Liquid	Liquid & Granular Soilds	Pressurized Gas	Cryogenic Liquid	? (Unspecified)	Cryogenic Solid	? (Unspecified)
		Insulation	Sun Shades	? (Unspecified)	? (Unspecified)	Multi-Layer Insulation (Exter	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Material Handling	Granular Solids	Pneumatics ('gasdynamic')	Auger / Screw Feeder	N/A	? (Unspecified)	Auger & Pneumatics	Pneumatics	Pneumatics (water as mediu
		Fluids (Liquid & Gas)	Pressure Differential	? (Unspecified)	Pressure Fed (by Heating)	? (Unspecified)	Pressure Differential	Pressure Differential	Pressure Fed (by Heating)
		Work Input	Shaft Work (Blower)	? (Unspecified)	Heating (Volume Increase)	? (Unspecified)	Shaft Work (Compressor & A	Steam Pressure Discharge	NEO Spin
Indirect ISRU	Avionics	Autonomy	Crewed (annual rotation)	Automated	Remote	Automated	? (Unspecified)	Automated	Crewed ('human labor')
		Computation	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Local Comms	? (Unspecified)	Transmitted	? (Unspecified)	Transmitted	Wired	? (Unspecified)	? (Unspecified)
		Deep Space Comms	? (Unspecified)	Laser Link	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Power	Electrical Generation	? (Unspecified)	Fission Reactor	? (Unspecified)	Photovoltaic Cells	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Energy Storage	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Thermal	Heating [Secondary]	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Resistance (electrical)	? (Unspecified)	? (Unspecified)
		Cooling	Radiator	? (Unspecified)	? (Unspecified)	Cold Plate	Ice Bath	Passive	? (Unspecified)
		Heat Exchangers	Conterflow Gasses	? (Unspecified)	? (Unspecified)	? (Unspecified)	Tubular	? (Unspecified)	? (Unspecified)
		Distribution	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Refrigerant Loop	? (Unspecified)	? (Unspecified)
		Beam Transmission	? (Unspecified)	N/A	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)	Mirrors ('reflectors')
	Wastes	Tailings & Overburden	Eject into Space (mass driver	Storage/Reuse	? (Unspecified)	Eject into Space	? (Unspecified)	Eject into Space	Eject into Space (spin out)
		Byproducts & Excess	Storage/Reuse	? (Unspecified)	? (Unspecified)	? (Unspecified)	Storage/Reuse	Storage/Reuse	? (Unspecified)
	Structures	Support Structure	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Positioning	Anchors & Guy Wire Net	Anchor / Harpoon	Friction with Excavator	? (Unspecified)	? (Unspecified)	Friction with Excavator	Guy Wires / Tensegrity
		Relative Motion	? (Unspecified)	RCS Thursters	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Cable Tension, RCS ('jet')
		Rotation Control	Wound Tether ('Bridle & Jeep	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Wound Tether, Friction
		Main Source:	Billingham et al., 1979	Andrews et al., 2015	Kuck, 1997	US 9266627 B1 (2016)	US 20180194626 A1 (2018)	Sonter, 1997	Gertsch et al., 1997
		(and title)	Space Resources and Space S	Defining a successful comme	Decision Points	Method, apparatus, and syst	Methods and Apparatus for F	The Technical and Economic	Mining Near-Earth Resources

Table 4-2: Existing NEO concepts characterized by morphological options (part 3 / 3)

20 Options Identified
v.5.1 7/15/2020

Key to Options: Option for Case Study | Null Option (not needed) | Violates Mission Assumpt. | Unspecified in Literature

Task	Group	Category	Deep Space Industries	Nallapu et al. (Arizona State)	Sommariva (Meta Consulting)	Gertsch et al. 'Cohesive and Hard Rock'	Kargel (USGS)	Benaroya (Rutgers University)
Sample Return	Integration	Separation	Subsequent Missions	Single Unit (None)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Swarming Craft
		Redunancy	Multiple Craft	Independent Strings	? (Unspecified)	? (Unspecified)	? (Unspecified)	Multiple Craft
	Return Vehicle	Thrust Class	Electrothermal (resistance)	Chemical Reaction (liquid)	Nuclear Thermal	Mass Driver	? (Unspecified)	Solar Sail
		Propellant	Water/Steam	Hydrolox	? (Unspecified)	N/A	? (Unspecified)	? (Unspecified)
		Chamber Reaction	N/A	? (Unspecified)	N/A	N/A	? (Unspecified)	? (Unspecified)
		Return Type	? (Unspecified)	Whole SoS	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
Direct ISRU	Prospecting	Local Observations	Precursor, Passive Observati	? (Unspecified)	Precursor Mission(s)	? (Unspecified)	Precursor, Passive Observati	? (Unspecified)
		Wave Type	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Visible, Infrared, Gamma	? (Unspecified)
		Sampling	Excavate (automated)	? (Unspecified)	? (Unspecified)	? (Unspecified)	Excavate (drilling)	? (Unspecified)
	Excavation	Containment	Synched Bag	? (Unspecified)	Localized Membrane ('cap')	Synched Bag	? (Unspecified)	Wire Mesh
		Cut Rock	? (Unspecified)	Rotary Cutter	Rotary Cutter (excavator)	? (Unspecified)	Optical Beam (laser drill)	? (Unspecified)
		Powderize	? (Unspecified)	? (Unspecified)	Crush (ground)	Explosives	? (Unspecified)	? (Unspecified)
		Sorting/Sizing	? (Unspecified)	? (Unspecified)	Centrifugal (rotate cap), Sieve	? (Unspecified)	Filtration, Centrifugal	? (Unspecified)
	Extraction	Heating [Primary]	Dielectric (microwave)	Resistance (electrical)	? (Unspecified)	? (Unspecified)	Light (laser drill)	? (Unspecified)
		Beneficiation	? (Unspecified)	? (Unspecified)	Magnetic Separation	Molten Powderization	Molten 'Lake', Magnetic Rake	? (Unspecified)
		Volatile Capture	? (Unspecified)		Condensation (distill), Sorbe	? (Unspecified)	Condensation (distilled)	? (Unspecified)
	Refining	Make Oxygen	N/A	Split Water	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Make Hydrogen	N/A	Electrolysis (Unspecified)	Electrolysis (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Crack Hydrocarbons	N/A	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Make Methane	N/A	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Quality Control	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Storage	Medium	? (Unspecified)	? (Unspecified)	Pressurized Gas	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Insulation	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Material Handling	Granular Solids	? (Unspecified)	? (Unspecified)	Conveyor Belt	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Fluids (Liquid & Gas)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Work Input	? (Unspecified)	? (Unspecified)	? (Unspecified)	NEO Spin	? (Unspecified)	? (Unspecified)
Indirect ISRU	Avionics	Autonomy	? (Unspecified)	? (Unspecified)	Automated	Crewed ('human labor')	? (Unspecified)	Autonomous
		Computation	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Local Comms	Transmitted	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Deep Space Comms	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Power	Electrical Generation	Photovoltaic Cells	Photovoltaic Cells	? (Unspecified)	? (Unspecified)	Photovoltaic Cells	Photovoltaic Cells
		Energy Storage	? (Unspecified)	Batteries	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Thermal	Heating [Secondary]	? (Unspecified)	Resistance (electrical)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Cooling	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Heat Exchangers	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Distribution	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Beam Transmission	Beamed Microwaves	N/A	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Wastes	Tailings & Overburden	Storage/Reuse	? (Unspecified)	? (Unspecified)	Eject into Space (mass driver	Eject into Space	? (Unspecified)
		Byproducts & Excess	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
	Structures	Support Structure	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)	? (Unspecified)
		Positioning	? (Unspecified)	Counter Rotating Wheels	? (Unspecified)	Anchors ('point'), Guy Wires	? (Unspecified)	Guy Wires / Tensegrity
		Relative Motion	? (Unspecified)	? (Unspecified)	? (Unspecified)	Cable Tension	? (Unspecified)	Cable Tension
		Rotation Control	? (Unspecified)	? (Unspecified)	? (Unspecified)	Wound Tether, Friction	? (Unspecified)	Friction with Containment
		Main Source:	Lewis & Gump, 2015	Nallapu et al., 2016	Sommariva, 2015	Gertsch et al., 1997	Kargel, 1994	Benaroya, 2013
		(and title)	Asteroid Mining 101: Wealth	Optimized Bucket Wheel Des	Rationale, Strategies, and Ec	Mining Near-Earth Resources	Metalliferous asteroids as p	Architecture for an Asteroid-I

Table 4-3: Augmented design space of morphological options by source

Task	Group	Category (Shaded by Source of Option)	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	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 Separatio	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 Electrolysi:	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 (Exte	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 Differentual	Flow Ionization	Jet (momentum transfer)			
		Work Input	Heating (Volume Increase)	Shaft Work (Pump, Blc	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		
	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		
		Beam Transmission	Fiber Optics	Mirrors	Beamed Microwaves				N/A
	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	Anchor / Harpoon	Guy Wires / Tensegrity	Friction with Excavatc	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	Wound Tether	N/A

Legend:
From Existing Concept
Existing Idea (ISRU & Spacecraft)
Different Field

only 6% of the rather large variation in functional completeness of concepts appears to be explained by the passage of time. More information on each concept is available in Appendix A. Note that concepts may have a valid reason for not needing to include a selection for some categories with a 'null' option selected. In other cases an option was selected that is incompatible with the selected mission, so it is excluded from the morphological matrix. Sometimes no selection was apparent from the documentation and no rationale was given, leading to an unspecified designation.

Table 4-4: Unspecified selections observed in existing NEO ISRU concepts

Concept Name ***(Organizational Affiliation)***	**Missing Selections**	**Functional Completeness**	**Primary Source**
Honey Bee APIS *(TransAstra Corp.)*	4	91%	[89]
Spider *(HoneyBee Robotics)*	4	91%	[88]
Robotic Asteroid Prospector *(Astrotecture/v$_\infty$/HoneyBee/New Space)*	6	86%	[81]
Cornucopia *(Star Technology & Research)*	6	86%	[153]
Hein et al. *(Initiative for Interstellar Studies)*	10	77%	[62]
RockBreaker *(Georgia Tech ASDL)*	12	72%	[146]
Konstantin & Mules *(Catalyst Corporation)*	13	70%	[155]
O'Leary et al. *(NASA Ames)*	14	67%	[156]
Surculus Astrum *(Univ. of WA Sr. Design)*	18	58%	[144]
Kuck 'Mosquito'	19	56%	[157]
(Planetary Resources)	19	56%	[39]
Carbonaceous Volatile Asteroid Recovery (CAVoR) system *(Pioneer Astronautics)*	21	51%	[38]
Sonter 'Best Near Term' *(Asteroid Mining Group)*	21	51%	[158]
Gertsch et al. 'Noncohesive Friable Rock' *(Missouri S&T)*	24	44%	[80]
(Deep Space Industries)	26	40%	[130]
Nallapu et al. *(Arizona State)*	26	40%	[145]
Sommariva *(Meta Consulting)*	30	30%	[159]
Gertsch et al. 'Cohesive and Hard Rock' *(Missouri S&T)*	31	28%	[80]
Kargel *(USGS)*	33	23%	[160]
Benaroya *(Rutgers University)*	34	21%	[161]
Mean	18.6	57%	Note: 43
Standard Deviation	9.7	23%	Categories

From assessing each of the existing concepts in Table 4-2, it was noted that significant gaps in functionality were present in all concepts. A summary of the number of missing selections for each concept is shown in Table 4-4. It was found that of the 43 subsystem categories identified, on average a design solution for 43% of them was not selected on average, one way or another. Of course, some concepts did much better than others, and some omissions far more egregious oversights than others. Neglecting to mention if rock will be crushed or not during extraction is one thing, but forgetting to consider any form of thermal management when evaporating gasses is inexcusable. Most commonly overlooked functionality by category is provided in Table 7-1 for reference.

4.3.2 Populating the Design Space

In addition to the existing concepts, morphological options were added based upon existing ideas in the field of spacecraft design or ISRU, and ideas taken from other fields. All proposed options are first checked for compatibility with the Selected Mission, then added to Table 4-3 where they are deemed a plausible fit to the functional niche. A total of 206 options across 43 categories were found, leading to 31.7 octillion (short scale) combinations without accounting for compatibility between options. More information on each morphological option is available in Appendix B, including definitions and examples. Note that though efforts have been made to include a wide variety of morphological options for NEO ISPP concepts, it is by no means a compressive set. Novel low TRL ideas are routinely proposed, and preference was given to options with higher perceived TRL within a category if more than six were identified. The selected mission also restricted the categories included, like limiting propulsion choices to chemical means for instance.

The majority of identified options come from examining how the eighteen existing concepts each fulfil the functional niches for subsystems identified, as shown in Table 4-2. Note that no one concept made a selection in every category, and only concepts compatible with the assumptions of the selected mission were used to populate options within the morphological matrix. 131 options (64%) from existing concepts were observed, including 14 null options.

Related concepts from the field of ISRU and spacecraft that were not included in the existing concept selections were also introduced into the morphological matrix. These ideas stem from observations about hardware used on flight missions, as well as published papers and presentations. 48 options (23%) from existing ideas in the field were found, including one null option.

Ideas from different fields were also included, with an eye towards potential technology transfer opportunities. These additional options tend to stem from mining and petrochemical industries. During the process of formulating a definition or researching other morphological options, functionally analogous techniques were often identified. In other cases, broad options were split up to be more specific as deemed appropriate from the sources available. 27 options (13%) from other fields were felt worthy of inclusion.

Note that there were a number of assumptions made for the compilation of the morphological matrix detailed herein. First, to make the number of morphological options considered to be more manageable, each morphological option is itself a broad category of technologies that could be a category in its own right. The most mature technology ('type example') that falls within the definition of the morphological option is assumed to adequately characterize the other technologies to a reasonable degree. Secondly, only options applicable to the selected mission of a NEO sample return mission using NEO-derived propellants are considered, as described in § 3.5. The main effect is that, only propulsion systems utilizing propellants produced via In-Situ Resource Utilization (ISRU) are considered to focus the analysis upon In-Situ Propellant Production (ISPP) System of System (SoS) design trades. Third, logistics are simplified by only considering missions with an unmanned robotic spacecraft preforming a single outbound trip and a single return trip, with some amount of equipment left behind on the NEO. Fourth, turnkey operation with prefabricated and preassembled systems with no possibility for repair is assumed, to simplify the analysis. A reliability analysis is not currently preformed, with the degree of redundancy and oversizing of the SoS being the tuning levers to assure continued operation. Fifth, only scientific regolith samples are returned to Low Earth Orbit (LEO) to avoid private property concerns under the Outer Space Treaty, excluding most metal processing methods. Sixth, biological processing methods are disallowed to avoid violating planetary protection protocols. This thesis does not claim to be a truly comprehensive source for all ISRU morphological options, though it should have more than prior works.

4.4 Technological Readiness Level Assessment

With the morphological matrix not populated with options for each category, the next step in research plan 2 is to estimate the technological readiness of the identified options. The primary goal is to ascertain how feasible an identified option is for implementation, by means of identifying a functioning system or one under development. This is being done to systematically down-select from a large number of morphological options, identify ideas for system trade studies, and to provide a ‘snapshot in time’ to aid future technology development efforts. Due to time constraints, the use of phenomenological inference upon available sources was conducted, instead of other methods such as surveying subject matter experts or checklists of necessary capabilities.

Since this is not a comprehensive assessment, the reader should note that the TRLs presented here are a rough approximation at best. Each morphological option is likely to have a plethora of ideas that fall under its definition, but only one can be described as the 'type example' for characterization. This search was also conducted entirely in the public domain by scouring the internet for scholarly sources and capabilities of businesses. It is entirely possible that the assessed technologies are farther along in classified or proprietary use cases meriting a higher TRL, or have been depreciated or discontinued meriting a lower TRL, without the author's knowledge. Note that TRLs decrease over time without active use, and even 'flight proven' technologies could merit a lower TRL if documentation is insufficient and/or the supply chain has been repurposed. This work tries to keep type examples to a time horizon within the last decade (2009 – 2019), though this is not always possible. Please keep in mind the limitations of this approach when using this information.

4.4.1 TRL Determination

To conduct the streamlined TRA documented in Appendix B, the following methods were used. First, relevant options from the morphological matrix had terminology coined, then were given a preliminary definition. Second, the literature is scoured to identify appropriate examples that fit the provided definition of the morphological option under consideration. If a good example is not found the option definition and name is revisited and iterated upon. If the example discovered is applicable but does not fit a new option is added, or a new category in rare cases.

Third, the most developed example found is selected to be the ‘type example’ that characterizes this option for either microgravity or terrestrial use cases. Microgravity use cases are considered to be applicable to deep space conditions within the vicinity of a Near Earth Object (NEO). As few technologies have been used in the vicinity of NEO, it is desired for the relevant fundamental physics to be preserved in the type example’s use case, such that similarity parameters could be used to relate hypothetical test data if available. On the flip side, terrestrial use cases are in the vicinity of Earth, and could be looked to as possible opportunities for technology transfer to microgravity applications.

Fourth, this type example is assigned a TRL based upon the description it appears closest to. Note that best guess for the TRL value achieved globally is used instead of a range, to best represent the state of the art and permit discrete logic operations. The TRL definitions used were taken from the U.S. Government Accountability Office (GAO) report GAO-16-410G, with the descriptions provided in Table B-1 based upon the U.S. Department of Defense (DOD) documentation [112, p. 17,131]. Note that the U.S. Department of Energy and U.S. National Aeronautics & Space Administration (NASA) also maintain similar TRL definitions with descriptions, with minor differences but similar intent. The DOD descriptions were selected to be used in this thesis, since they applied most broadly to both hardware and software, and were emphasized by the GAO.

Fifth, the last three steps are repeated to find a second type example for the use case (terrestrial or microgravity) that was not already assigned a TRL. Lastly these decisions are documented and referenced, before continuing. To these ends, a type example for each morphological option was sought for both terrestrial and microgravity applications, in order to roughly characterize the TRL of the morphological option being discussed in accordance with Table B-1.

4.4.2 Screening with TRLs

Once a sufficient number of TRLs are determined for morphological options with a category they can start to be used a as a point of comparison. Due to the nature of TRLs, it is worth noting that the difficulty in the down-selection lies more in setting up the problem correctly than it does in preforming the selections. It is best to have all morphological options within a category assigned TRLs before conducting this screening step, though that may not always be the case. In the presence of missing values, it is recommended to either exclude options from consideration or to take an educated guess to be revisited latter.

To conduct TRL screening, absolute TRL values are compared within a category to rank the corresponding morphological options in decreasing order. Higher TRL values are perceived as better, due to the assessed technology being more mature. The first consideration for the superior options is a higher microgravity TRL, overruled only if it is judged to be incompatible. The second consideration is a higher terrestrial TRL, though there is expected to be less variation in the result. It is important to note that TRLs are an ordinal but not continuous metric, as steps between levels are not equal. A greater TRL value implies a technology is further along the path for development in a given use case. A greater than or less than comparison is meaningful, but subtracting TRLs is not. Judgement calls can still be made based upon other factors when selection occurs.

Table 4-5: Morphological matrix with microgravity Technological Readiness Levels shaded

Task	Group	Category (Shaded Options)	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 (Voltage)	Alkaline Electrolysis (Voltag	Solid Oxide Electrolysis (Vo	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 (Exte	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, Blower,	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
	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		
		Beam Transmission	Fiber Optics	Mirrors	Beamed Microwaves				N/A
	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	Wound Tether	N/A

Shading Selector:

None
Terrestrial
Microgravity

Legend (TRL):
(TBD)
1
2
3
4
5
6
7
8
9
N/A

Table 4-6: Morphological matrix with terrestrial Technological Readiness Levels shaded

Shaded Options

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 (Voltage)	Alkaline Electrolysis (Voltag	Solid Oxide Electrolysis (Vol	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 (Exte	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, Blower,	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
	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		
		Beam Transmission	Fiber Optics	Mirrors	Beamed Microwaves				N/A
	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	Wound Tether	N/A

Shading Selector:

None
Terrestrial
Microgravity

Legend (TRL):
(TBD)
1
2
3
4
5
6
7
8
9
N/A

Table 4-7: Selected concepts with microgravity Technological Readiness Levels shaded

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	Visible Light	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	Filtration	Filtration	Filtration	Filtration
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)
		Beneficiation	N/A	Centrifugal (Density)	Centrifugal (Density)	Centrifugal (Density)	Centrifugal (Density)
		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, Blower,	Shaft Work (Pump, Blower,	Shaft Work (Pump, Blower,	Shaft Work (Pump, Blower,
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
	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
		Beam Transmission	Mirrors	N/A	N/A	N/A	N/A
	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 Selector:

None
Terrestrial
Microgravity

Legend (TRL):
(TBD)
1
2
3
4
5
6
7
8
9
N/A

Italics are 'best guess' on design intent

4.5 Selected Baseline Concept

When it comes to making the selections themselves, the first step was to partition needed functionality for each propellant type. Decisions are made to determine which functions were not needed for the given propellant type, with null values being selected. This primarily describes the refining system and return vehicle functions. The next step is to select an option for each morphological category largely based upon the TRL screening technique in the last section, with higher TRL options given additional consideration. When possible due to perceived compatibilities, common functions are selected to simplify the sizing code to be constructed with more common elements. When TRLs prove insufficient to select an option, consultation with expert judgement is recommended.

Though the TRL screening filter is helpful as a first pass, it is also important to consider other knowledge about the operating conditions for the function at hand. Selections made that do not follow the recommendations of the TRL screening step, or among equivalently ranked options, are explained as follows:

- Single unit separation was assumed to simplify operations and material handling.
- Redundant cross-strapped strings were selected to reduce the loss in functionality from any one failure.
- Return vehicle propulsion and chamber reaction were selected based upon perceived compatibilities with the propellant type.
- Active observation with ground penetrating radar was selected in hopes of being able to better characterize the interior of the NEO from orbit.
- Infrared lamps for primary heating during extraction were selected to have radiative heat transfer instead of convection, to avoid the need to pressurize the chamber with a carrier gas which would latter need to be filtered out.

- Pyrolysis was selected to crack hydrocarbons due to cross-functionality with the spalling induced by radiative heating from extraction.
- Process monitoring was selected for quality control since experimental scientific instruments would likely have a lot of sensors included anyway.
- Storage medium was selected based upon compatibility with the propellant type, and to maximize the perceived ratio of propellant density to storage tank mass.
- Multi-layer insulation was perceived to permit the least radiative heat transfer into the tankage of TRL 9 options.
- Pumps and augers were selected for material handling to permit finer control, and to facilitate batch extraction in a sealed thermal vacuum chamber for increased volatile recovery.
- Automated avionics were selected to have some controls be executed locally, yet reduce required bandwidth use for data links from operations on Earth.
- Distributed avionics connected by wiring were selected to complement cross-strapped redundancy and single unit separation.
- Photovoltaic cells and batteries were selected in recognition of strong solar irradiation in the inner solar system and to avoid the need for radioactive materials.
- Radiators were selected in recognition of high cooling requirements and the desire to avoid venting from consumable use or dumping heat in the NEO.
- Finned radiators with refrigerant loops were selected in anticipation of high demand for heat transfer throughout the SoS.
- Wastes are all stored, to minimize debris released which could damage the spacecraft or cling to surfaces like solar panels and radiators.
- Panel support structures were selected with orbital replacement unit boxes in mind.
- Microspines on articulated robotic arms were selected to complement corers for extraction. Corers are expected to provide better anchoring via friction in less cohesive rock, with microspines expected to preform better on more cohesive rock.
- Selective ablation was selected for rotation control to permit possible dual functionality of subsystems with radiative heating in extraction.

Selections made are shown in Table 4-7. Note that the most functionally complete existing concept identified in Table 4-4, the TransAstra Honey Bee, is included for comparison though slightly tweaked to no longer have missing selections.

Table 4-8: Microgravity TRLs below a given threshold for selected concepts in descending order, as compared to a tweaked form of the TransAstra HoneyBee

Concept Name	Propellant	TRLs ≤ 7	TRLs ≤ 5	TRLs ≤ 3
Honey Bee {Tweaked}	*Steam*	13	10	4
Concept 'MO'	*Methalox*	11	6	1
Concept 'S'	*Steam*	11	6	0
Concept 'H'	*Hydrogen*	10	5	0
Concept 'HO'	*Hydrolox*	9	4	0

The four sized concepts are compared to each other, and the most developed NEO ISRU architecture within Table 4-8. Based upon an analysis of the TRLs identified in Table 4-7 for these options, it immediately stands out that concept 'HO' corresponding to the hydrolox propellant type has been assessed to contain relatively fewer low TRL subsystem options than the other concepts, it has been selected as the baseline concept for comparison.

Result 2 (R2)

The hydrogen-oxygen (hydrolox) propellant design selected through narrowing down options using Technology Readiness Levels (TRLs) should be a better baseline for comparison than the Honey Bee concept.

CHAPTER 5. QUANTITATIVE DESIGN ASPECTS: CONCEPTUAL SIZING

With the design space qualitatively characterized and a baseline concept selected, the next step is to quantify the performance of concepts for comparison. This process has three main steps, as described in § 3.3 – Quantitative Aspects. First, important input parameters should be found, with reasonably expected input ranges determined from the literature. Secondly, modular sizing code modules corresponding to the selected morphological options are to be developed. Verification efforts will also be described as appropriate. Third, meaningful performance metrics to output from the sizing code for comparison shall be formulated. In this way, conceptual trades can be quantified.

5.1 Capturing Inputs for Modeling

This first step revolves around quantifying various attributes of the selected mission sufficiently to act as inputs into the sizing code. It is desired to have a small set of required inputs which captures all necessary information to make discerning trends more manageable. Research question 3 (Q3) summarizes this sentiment. Note that the scope of this thesis is restricted to modeling ISPP related activities in the vicinity of NEO as in Figure 2-4, which helps reduce the number of inputs considered scope the analysis.

Research Question 3 (Q3)

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

Note that the set of parameters being developed here shall be referred to as the 'required' inputs, with nominal values and ranges that can be reasonably expected to occur. In contrast, additional 'optional' inputs for tuning the model shall be created as needed while developing the sizing code, though only reasonable default values will be sought for these. Both are accessible by passing updates into the sizing code, though the required inputs are expected to be more subject to change. With the selection of different NEO to be the destination, those properties are expected to be the ones most subject to change and thereby affect sizing efforts the most. Three key aspects of NEO are considered herein: mission parameters, solar radiation effects, and volatile composition.

5.1.1 Mission Parameters

NEO Orbital parameters relating to the mission can be simplified into a typical NEO mission profile, with an Aten-type orbit shown in Figure 5-1. The mission phases consist of the following: LEO departure, NEO arrival, time on station or 'mining season', NEO departure, and LEO arrival [75]. Note that it is assumed that a single trip is sent to/from the NEO, orbits of small inclination used, and Earth launch/EDL constraints are excluded. An Aten-type orbit is shown, for latter reference. Similarly, the return of mass from an asteroid can be understood as delivering a payload on a rocket from a NEO. Activities occurring on NEO are understood to be within a microgravity environment. To simplify matters in line with space logistics community convention, the starting and ending points of the mission shall be restricted to Low Earth Orbit (LEO) to 'decouple' the launching and landing design decisions from the activities in space [24], [26]. Some of these sun centered orbits are shown in Figure 5-2 to the left. In addition, the three-body problem permits additional, stranger orbital solutions for NEO, as seen in Figure 5-2 to right [162].

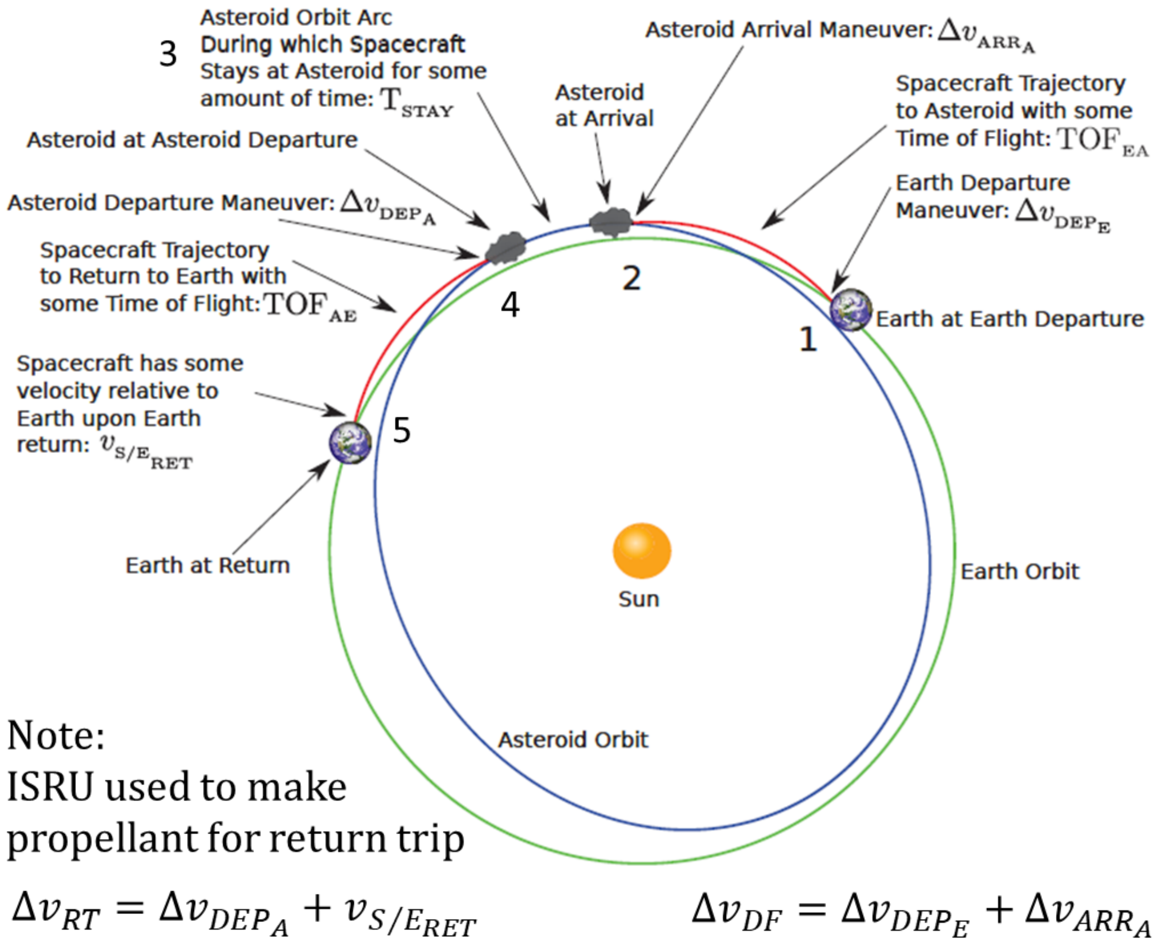
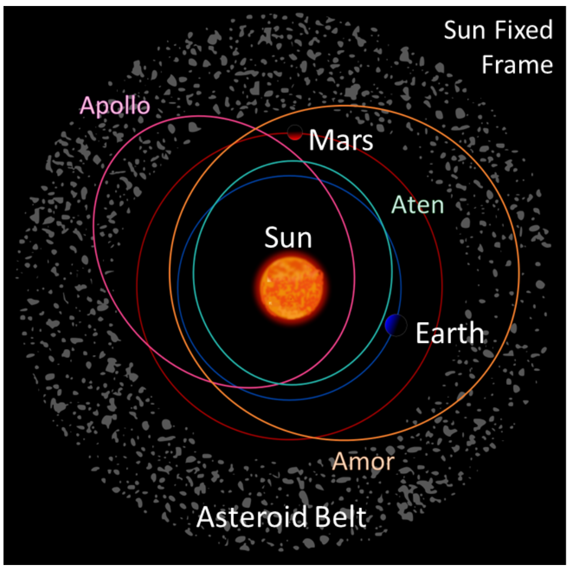


Figure 5-1: Simplified typical NEO mission of Aten-type (modified from [75])

The sun fixed frame to the left in Figure 5-2 takes the perspective that the sun is assumed to be in a fixed location and is treated as the origin, with the relative motion of the other objects plotted with respect to the sun. In this way, the orbits of NEO are seen in relation to a map of the inner solar system. Not shown are comets, the orbits of which are similar to the Apollo type shown, but characterized by a significantly increased eccentricity. The Earth co-rotating frame to the right in Figure 5-2 takes the perspective that the sun is fixed in space as the origin, with the angular velocity of the earth subtracted from the relative motion of all the other objects plotted. In this way, the orbits of a separate set of NEO are seen relative to Earth's own orbit. The most notable of these co-orbital groups are the Earth Trojan asteroids, which are in orbit about an Earth-Sun Lagrange point. Lagrange points occur where the gravitational forces of two more massive bodies effectively cancel out [163]. These Earth Trojan orbits are also the most stable and have the most NEO in them of the co-orbital orbital types, and are thus the primary co-orbital orbits considered herein [162]. The other co-orbital types can be perturbed by gravitational effects of other massive bodies in the outer solar system, the gas giants.



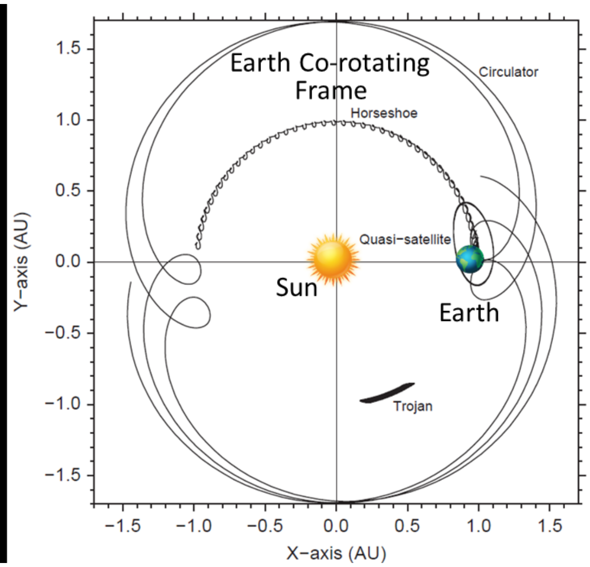


Figure 5-2: Types of NEO – Earth approaching orbits on left (ESA 2013), and co-orbital objects on right (annotated [162])

These NEO orbital classes have been distinguished and characterized to note the variety of NEO orbits. Most of these orbital classes are fairly well known, and have corresponding low-energy transfer orbit solutions to and from Earth that are well characterized. Generally speaking, the more elliptical or inclined the transfer orbit is the greater Δv required to conduct the maneuver. Transfer orbit solutions for sample missions have been reported in the literature for both impulsive Holman and continuous thrust propulsion systems [99], [105]. Note that the metamorphic asteroid Itokawa visited by JAXA Hayabusa is in an Apollo-type orbit, as is the carbonaceous asteroid Ryugu that

JAXA Hayabusa 2 is visiting. However the carbonaceous asteroid Bennu that NASA OSIRIS-REx is visiting is an Earth Trojan-type. A few categories of variants upon the typical mission profile in Figure 5-1 are identified below:

Types of mission profiles for NEO rendezvous and return [99], [104]:

- Apollo-type: high eccentricity orbits, short time on station near aphelion
- Comet-type: high eccentricity orbits, very short time on station near perihelion
- Aten-type: long time on station from roughly aphelion to perihelion
- Arjuna type: spiral low thrust transfer orbit, intermediate time on station
- Inclined-type: high inclination and low eccentricity orbits

Though these five types of mission profiles have been identified from the literature, examining their trajectories is beyond the scope of this thesis, which restricted itself to NEO proximity operations. Instead, parameter ranges that capture variation across the identified mission types to use as inputs for sizing are desired.

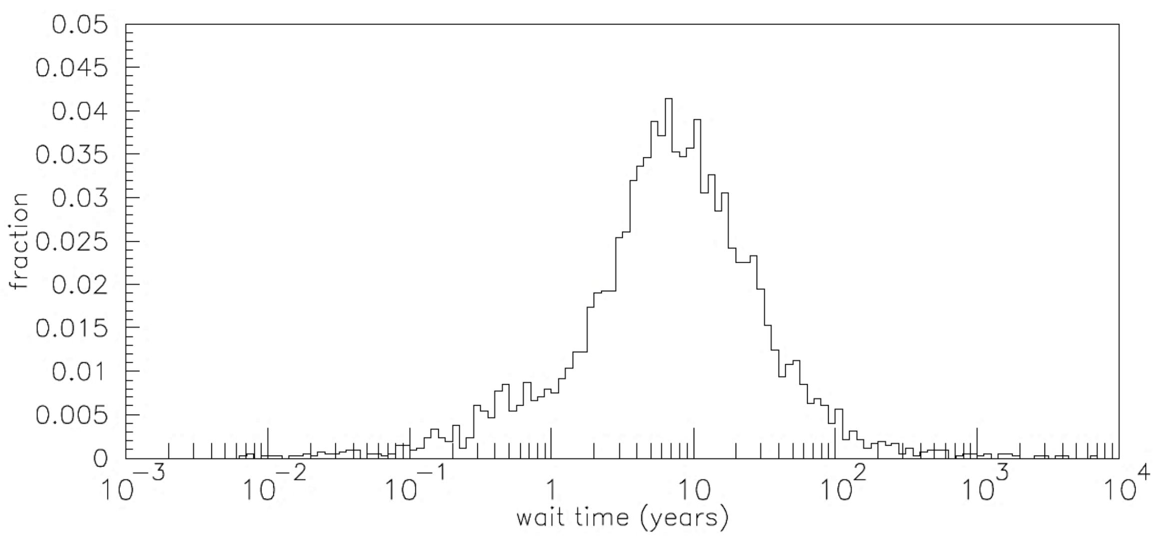
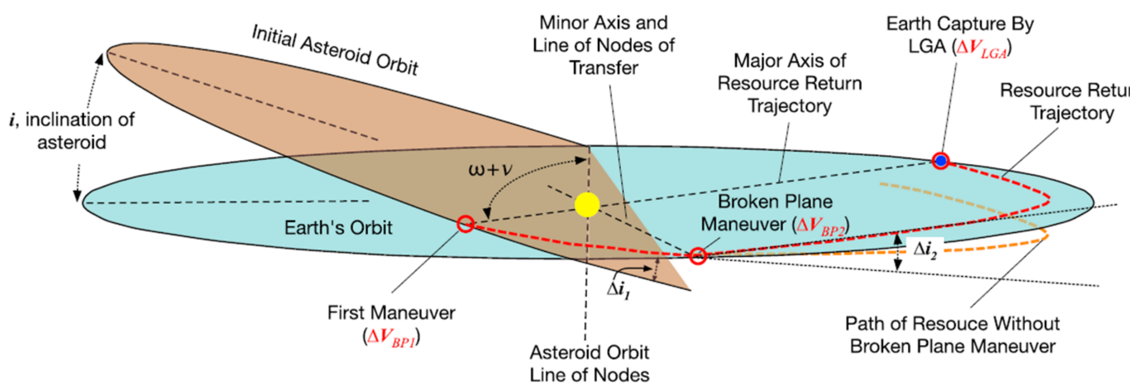


Figure 5-3: Probability distribution of time on station when waiting for ideal orbital transfers from NEO to LEO with return $\Delta v \leq 3$ km/s [164]

Mission profiles can be categorized as having aphelion-centered, perihelion-centered, or extended 'mining seasons', termed as the time on station in this thesis [104].

It is worth noting that among these mission type variants, the available time on station to be used for propellant production varies significantly. This observation is quantified with a probability distribution for NEO low energy return trajectories in Figure 5-3 [164]. These values were computed for return trajectories utilizing a broken plane inclination change and a lunar gravity assist, as shown in Figure 5-4. It can be seen here that if waiting for a low energy return trajectory, there may be a wait between arrival and departure ranging from months to decades. Trying to avoid an overly extended stay to return samples in a timely fashion, a range of time on station values 30 days $\leq t_{STAY} \leq$ 365 days with a nominal value of 100 [Earth] days seems to be reasonable based upon Figure 5-3.



Symbol	Element	Unit	Earth	Spacecraft broken-plane 0	1 (eqn. #)	2 (eqn. #)
a	semi-major axis	au	$a_E = 1$	a_0	a_1 (9)	$a_2 = a_1$
n	mean motion	deg/day	$n_E = 180\ k^{\ddagger}/\pi$	n_0	n_1	$n_2 = n_1$
e	eccentricity		$e_E = 0$	e_0	e_1 (10)	$e_2 = e_1$
i	inclination	deg	$i_E = 0$	i_0	i_1 (3)	$i_2 = 0.0$
Ω	ascending node	deg	$\Omega_E = 0$	Ω_0	Ω_1	$\Omega_2 = 0.0$
ω	argument of perihelion	deg	$\omega_E = 0$	ω_0	ω_1	ω_2
$\tilde{\omega}$	longitude of perihelion	deg	$\tilde{\omega}_E = 0$	$\tilde{\omega}_0$	$\tilde{\omega}_1$	$\tilde{\omega}_2$
M_0	mean anomaly at epoch	deg	$M_E = 0$	M_0	M_1	M_2
t_0	epoch	MJD	$t_0 = 57653.835069$	t_0	t_1 (2)	t_2

‡k represents the Gaussian gravitational constant.

Figure 5-4: Broken plane maneuver and its orbital parameters [164]

In addition to the time on station, the change in velocity required for different segments of the mission is also of interest. After all, Figure 5-1 be simplified into a set of notional impulsive burns and the time between them. The segment returning from a NEO to LEO with corresponding Δv_{RT} is more of interest than the outgoing segment from LEO to NEO, since in-situ produced propellant is intended for use on the return trip. Note that the diverse NEO options and orbital dynamics are not the focus of this study, and their details can be largely captured using generalized mission profiles already outlined. Still, there are many ways to compute the change in velocity to return with disagreement between sources as to how much it should be. Ranges of NEO Δv between 0.5 – 3.0 km/s [164], 0.5 – 5.0 km/s [165], and 3.8 – 27 km/s [76] have been put forward. It is worth noting that close to a thousand NEO are believed to have $\Delta v \leq 3\,\mathrm{km/s}$ for return as shown in Figure 5-5, keeping the lower end of the range relevant [164]. It was thus decided to utilize the range $0.5\,\mathrm{km/s} \leq \Delta v \leq 5\,\mathrm{km/s}$, with the higher value source from the NASA Jet Propulsion Laboratory used for the nominal value of 4646 m/s for Ryugu [76].

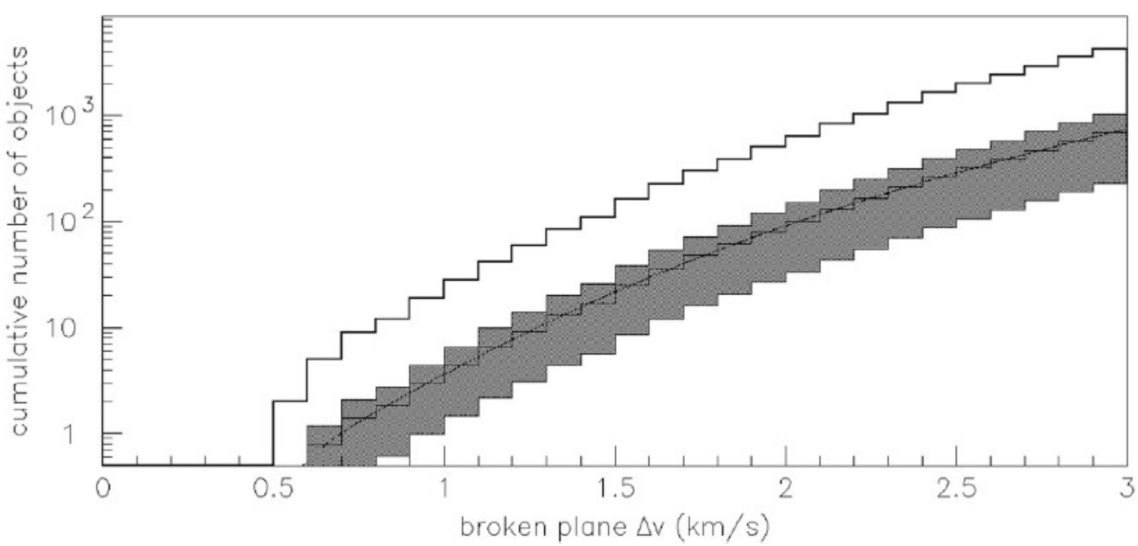


Figure 5-5: Cumulative known NEO with respect to return Δv [164]

5.1.2 Solar Radiation Effects

As useful as it is to know the time on station and change in velocity for return, knowing these characteristics is not sufficient to model the effect of solar radiation upon the NEO. Too much information is lost when computing the change in velocity for return from orbital parameters for this purpose. Probability distribution functions (PDFs) for NEO orbital parameters used to compute the values in Figure 5-5 are shown in Figure 5-6. [164].

The physics of radiation dictate that the radiative flux from a point source scales with the inverse square of the distance [166]. One method to conservatively size a design is to take the maximum expected load as the capacity to size to. Since the worst case scenario for the cooling system is the maximum irradiation, the minimum heliocentric distance D_{min} $[AU]$ reasonably expected during the mission is required. Since the worst case scenario reasonably expected for the heating system or solar power is a state of minimum irradiation, the maximum heliocentric distance D_{max} $[AU]$ is required, as well as something to account for diurnal cycles of light and darkness.

Looking at the orbital parameter data available in Figure 5-6, the perihelion and aphelion of the NEO form a good guess for the minimum and maximum heliocentric distances expected during the mission. Note that this distinction between the orbital states of the NEO and the states observed by the spacecraft is made since the spacecraft may not be expected to be operational for a full orbit of the NEO around the sun permitting design to more benign conditions. Alternately, the transfer trajectories used may place the spacecraft further or closer to the sun than the limits of the NEO orbit itself, calling for more restrictive values for sizing. With these disclaimers in mind, the destination NEO perihelion and aphelion will be assumed to be valid values for the minimum and maximum heliocentric distances unless otherwise more pertinent information becomes available. Based upon the probability distributions in Figure 5-6, a reasonable range for the minimum heliocentric distance is felt to be $0.75\text{ AU} \leq D_{min} \leq 1.2\text{ AU}$, with a nominal value of 0.9633 AU corresponding to Ryugu [164], [167]. Similarly, a reasonable range for the maximum heliocentric distance is felt to be 0.85 AU $\leq D_{max} \leq 1.45$ AU, with a nominal value of 1.4159 AU corresponding to Ryugu. Note that the maximum heliocentric distance must be greater than the minimum by definition.

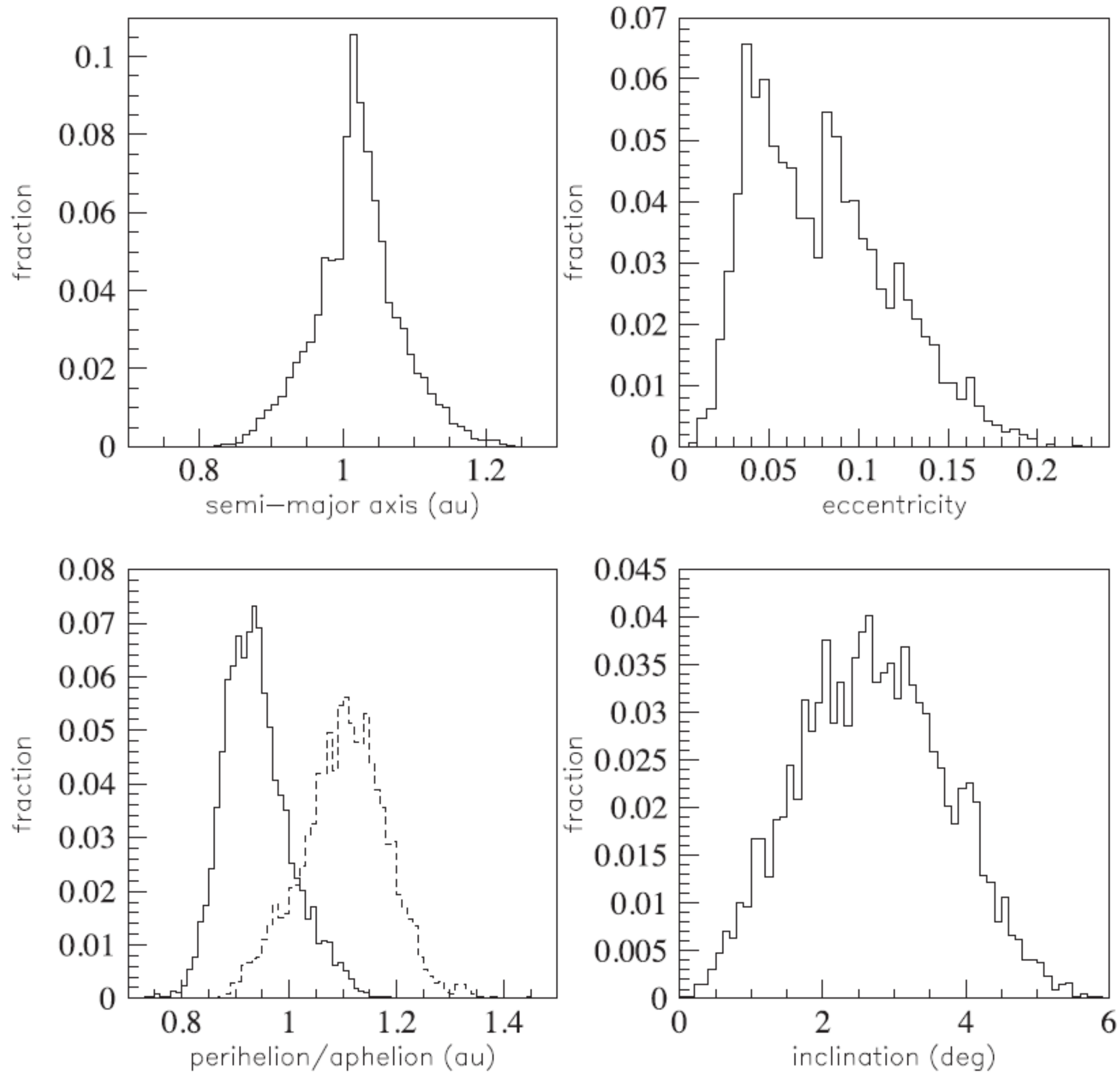


Figure 5-6: Orbital parameter probability distributions for known NEO with return $\Delta v \leq 3$ km/s [164]

Another aspect of sizing thermal management and solar power on a NEO is its diurnal cycles of light and dark, especially when operating anchored to the NEO surface. A common way to express the length of these diurnal cycles is the period of rotation in hours of a NEO about its axis, or a corresponding spin rate per day. This period can be determined via remote observation, though it is more difficult to observe than the orbital characteristics, so relatively fewer data points are available [168]. A histogram of NEO spin rates is shown in Figure 5-7 [169]. Based upon this information, a reasonable range of NEO periods of rotation is felt to be $(\sim 10\ \mathrm{d}^{-1})$ $2.5\ \mathrm{hr} \leq \mathrm{t}_{\mathrm{PERIOD}} \leq 24\ \mathrm{hr}$ $(1\ \mathrm{d}^{-1})$, with a nominal value of 7.6326 hr for Ryugu [167], [169].

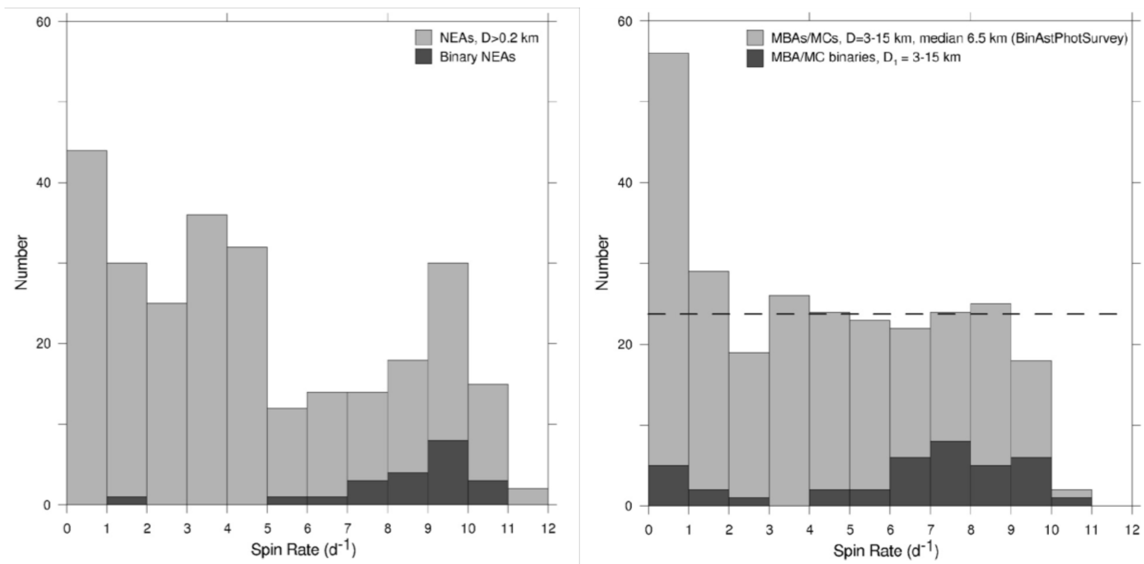


Figure 5-7: Spin rates of near-Earth (left) and main belt (right) asteriods [169]

5.1.3 NEO Volatile Composition

With measures of how the destination NEO moves in space reasonably captured, the next step is to parameterize what the NEO is made of. This NEO composition assessment being done with an eye to the availability of evolved volatile gasses, since these are the feedstocks for propellant production. As part of the analysis of space resources availability in § 3.5.1, Bell superclasses were introduced to classify NEO, with other taxonomy schemes mentioned. Plots of relative frequency of both Bell superclasses and Tholen types versus mean heliocentric distance are provided in Figure 5-8 on the left [124]. It was determined that the use of carbonaceous ‘primitive’ asteroids was most likely among Bell superclasses considered to provide the most volatiles for propellant production outlined in the selected mission. Tholen C-type, D-type, and P-type are noted to be members of the primitive Bell superclass in Table 3-1.

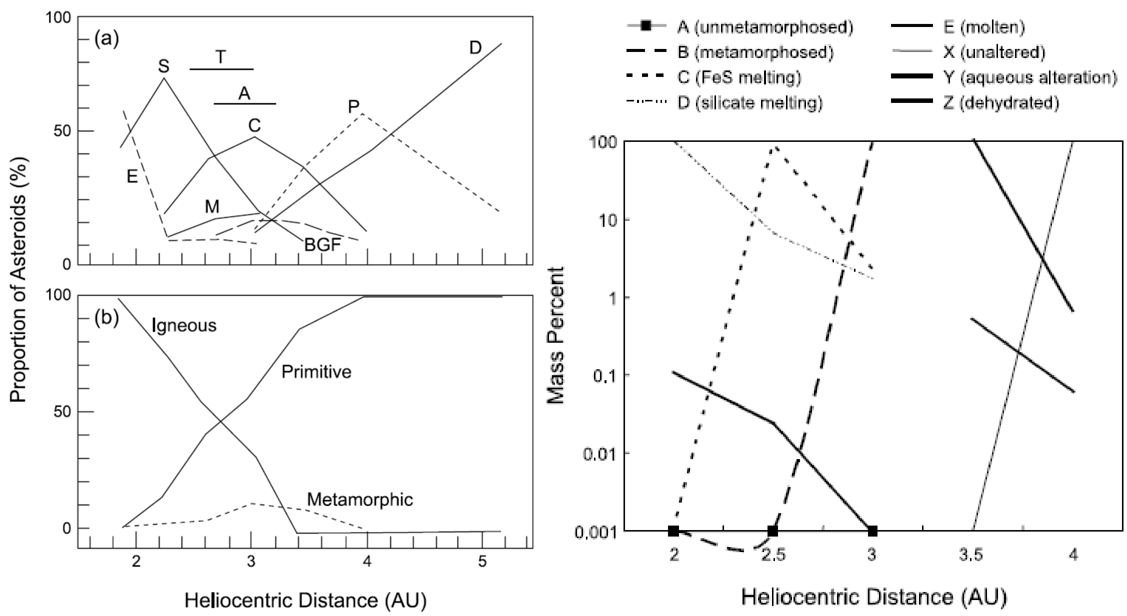


Figure 5-8: Asteroid frequency by Tholen type with respect to mean heliocentric distance on left, and mass percent of hypothesized geology on right [124]

Looking at Figure 5-8 though, Tholen C-type appears far more common than P-type and D-type in the inner solar system. This observation is borne out in the similar Bus-DeMeo taxonomy, with C-class, D-class, and some X-classes considered analogous to the Tholen types of interest [116]. In Figure 5-9, Bus-DeMeo C-Class Near Earth Asteroids (NEA) are noted to be significantly more common than D-class and X-class.

Among members of the primitive Bell superclass, it appears the selection of a Bus-DeMeo C-class as the destination offers the most candidates for possible destinations. It is also worthy to note that the igneous Bell superclass is the most common NEO composition, including the Tholen S-type in Figure 5-8 and analogous Bus-DeMeo S-class in Figure 5-9. This is thought to be a consequence of asteroid formation theory, with more intense heating closer to the sun sublimating volatiles and melting rock [124]. Heating is thought to stem from solar irradiation as well as changing electromagnetic fields and radioactive decay (^{26}Al, ^{60}Fe), implying that NEO composition is dependent on both location history and its previous composition. In addition, solar wind and dust attracted by microgravity are thought accrete small amounts of light elements on the surface of NEO over time [170]. These observations lend credence to NEO composition possibly varying with depth, and therefore doubts as to the ability of spectroscopy of the surface to provide detail on bulk NEO composition. On the other hand, hypervelocity impacts between NEO are theorized to disintegrate impactors, with the reformed celestial bodies being more homogenous in composition.

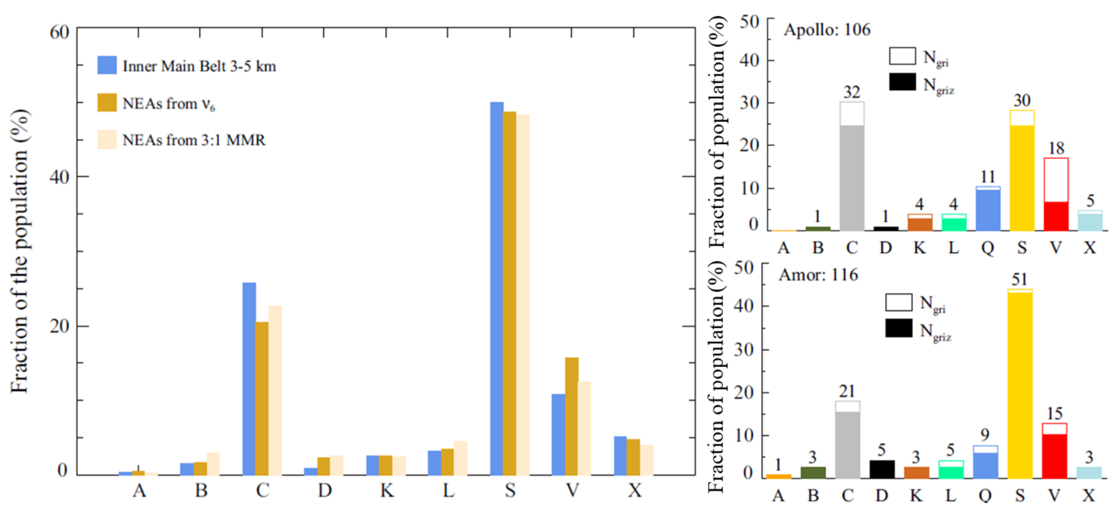


Figure 5-9: Relative frequency of NEO by Bus-DeMeo class and orbit type [168]

It is thus little surprise to note that determining the bulk composition of NEO is noted to be a tricky subject, especially when compounds containing light elements are considered [171], [172]. Research into NEO composition currently quite rudimentary due to the lack of pristine samples, making data hard to find to model. Sample return missions are the gold standard, but take a long time to conduct and require an outsize amount of effort for each NEO examined. Although to sample return missions to Bus-DeMeo C-type NEO are ongoing at press time (JAXA Hayabusa 2 and NASA OSIRIS-REx), chemical analysis of returned samples is still several years out.

Meteorites provide an interesting but fraught way to gauge potential bulk minerology of NEO, as meteorites got so close to Earth that they fell to its surface. Unfortunately, they are not representative of the overall population, especially for the primitive Bell superclasses. Reentry heating drives off volatiles and provides heat and pressure to alter allotropes and grain structures present, not to mention environmental contamination from being found on (or in) the ground after an unknown period of time has elapsed. Meteorites are still a decent start for obtaining mineralogy data though, with observable spectra mainly able to tell select details about chemical composition from afar [50]. A few hypothesized mappings between meteorites and Tholen asteroid types are shown in Table 3-1.

All of these studies on NEO composition have led to the development of asteroid simulants, which mimic the qualities of a material to enable more extensive empirical studies. This is especially important to ISRU development efforts, as these simulants can be used to test and improve prototypes on the ground. Lunar and Mars simulants have existed for some time, but the first commercial asteroid simulant was developed in 2017 by Deep Space Industries and the University of Central Florida [173]. It is important to note that different simulants mimic different things, and not all capture whole picture [49], [173]. For example a texture simulant might have the wrong dielectric properties, or a chemical composition may not match the mechanical grain structure.

In contrast to the proliferation of Lunar and Martian regolith simulants, only a select few asteroid simulants are known to be available. A series of Bus-DeMeo C-type regolith simulants were developed in 2017 by the Center for Lunar and Asteroid Surface Science at the University of Central Florida in partnership with Deep Space Industries with NASA funding [49]. Of particular interest is the 'CI' asteroid simulant, with the minerology reported in Table 5-1 reflecting the current best guess about replicating C-type asteroid composition with terrestrial materials [50], [151].

Table 5-1: Chemical species of CI Asteroid Simulant [174]

Mineral	***Weight %***	***Notes***
Antigorite	48.0%	A serpentine mineral, $(Mg,Fe^{++})_3Si_2O_5(OH)_4$
Epsomite	6.0%	Magnesium sulfate heptahydrate – $MgSO_4 \cdot 7(H_2O)$
Magnetite	13.5%	Iron Oxide – Fe_3O_4 (actually present 14.5%)
Attapulgite	5.0%	AKA palygorskite, $(Mg,Al)_2Si_4O_{10}(OH) \cdot 4(H_2O)$ This clay binds strongly without swelling/shrinking
Olivine	7.0%	Magnesium Iron Silicate – $(Mg_{0.9}Fe_{0.1})_2SiO_4$
Pyrite	6.5%	Iron Sulfide (FeS_2)
Vermiculite	9.0%	A smectite-group clay $(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2 \cdot 4H_2O$
Coal	5.0%	Sub-bituminous coal is a kerogen substitute

After Deep Space Industries was bought out by Consensys and divested its simulants business, CLASS inherited the intellectual property and manufacturing equipment and set up Exolith Lab to continue producing the simulants. Material safety data sheets are available on their website along with additional information such as the volatile release pattern shown in Figure 5-10 [175], [176].

Thus, a C-type NEO will be selected for inclusion in the baseline mission, with the CI asteroid simulant's chemical composition being used as the baseline chemical species of the C-type NEO for the model, due to being the best source of information currently available. It should be noted that although terrestrial minerals are used in the CI simulant, one of the main properties it was designed to mimic was the elemental composition of a CI meteorite, standing in for a C-type NEO. [49], [50], [151]. It is also noted that framing the question of bulk composition in terms of elemental chemistry instead of minerology is more easily translated into the chemical reactions which need to be modeled within the extraction and refining systems of the sizing code.

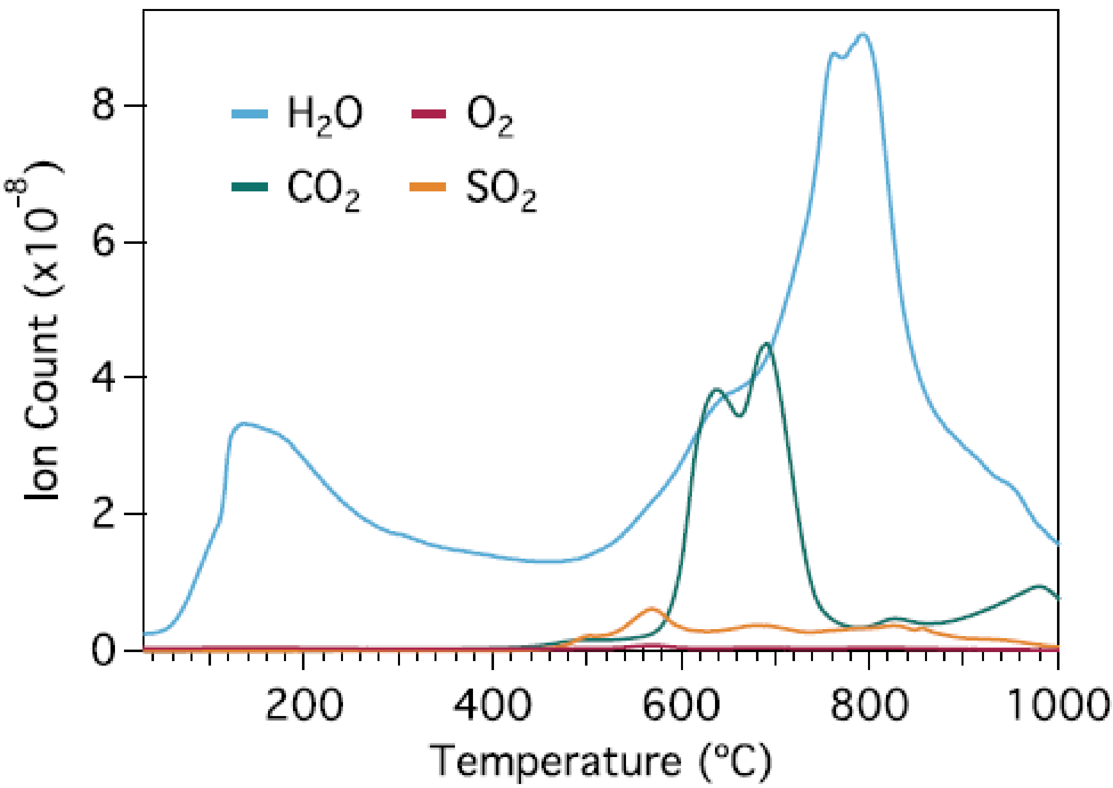


Figure 5-10: Volatiles released heating the CI asteroid simulant [176]

For the elements to be represented in the parameterization of composition, a priority is placed upon elements represent in the evolved volatile gases that are to be refined into propellant. With methane as a propellant choice, the elemental composition of carbon and hydrogen are both necessary parameters. Authorities have noted that some impurities should be included in the processing framework to make it more realistic, with sulfur being the top recommended candidate [91]. Figure 5-10 bears this out, with sulfur dioxide being the third most common evolved volatile after water and carbon dioxide, thus meriting the inclusion of elemental sulfur as a parameter. Oxygen was also considered as a parameter, though it was observed to almost always be present in excess of the amount required for oxides of all the elemental carbon, hydrogen, and sulfur present [151]. This input was felt a s redundant, and thus omitted to have metals, silicates, and oxygen to be assumed as the balance of the elemental breakdown.

From the data provided while developing the CI simulant, it is determined that reasonable nominal elemental mass fractions are 3.22%wt carbon atoms, 2.02%wt hydrogen atoms, and 5.25%wt sulfur atoms [151]. Appropriate ranges for the elemental composition to be allowed to vary in are more of a judgement call laden with assumptions. As explained in § 5.2.4 on extraction sizing, the decision was made to simplify the analysis by assuming that all elemental hydrogen is evolved as water, all elemental carbon evolved as carbon dioxide, and all elemental sulfur evolved as sulfur dioxide. Furthermore it was assumed that only these three chemical species were evolved as gasses, in quantities proportional to their relative cumulative emissions extrapolated from Figure 5-10.

By restricting the three evolved oxide species to less than 100%wt of the parent ore, possible combinations of elements comprising low-grade and high-grade NEO ores could be formulated. A minimum of 0.5%wt was assumed for elemental hydrogen and carbon to avoid failed cases by ensuring there will always be a small amount of the feedstocks necessary for methalox production. The maximum water in the ore was selected to be 98%wt corresponding to 5.49%wt elemental hydrogen since ice could conceivably be found, but so that the minimum amount of carbon dioxide can still be present. The maximum carbon dioxide in the ore was selected to be 55%wt corresponding to 15%wt elemental carbon, representing potential pyrolysis of a moderate length hydrocarbon compound. The elemental sulfur impurity levels were selected to around double the nominal value to be 10%wt (20.6%wt sulfur dioxide), with the floor set at no sulfur present. To make the trades between processing high-grade and low-grade ores more reasonable, an optional parameter relating to the quantity of overburden excavated but not extracted to represent possibly locally higher concentrations was created, though it is zero by default.

5.1.4 Selected Input Parameters

Based upon the preceding analysis about many aspects of how NEO affect the selected mission, a list of nine parameters has been arrived at. It is believed that by varying these values, the effects of mission parameters, solar radiation effects, and NEO composition can be adequately captured.

$PROP\_TYPE$	[String]	Chemical species to be produced by SoS
Δv_{RT}	[km/s]	Change in velocity to travel from a specific NEO to LEO
t_{STAY}	[days (Earth)]	Time of the stay at the NEO, between arival & departure
m_{SAMP}	[kg]	Mass of the sample to be returned from NEO to LEO
D_{min}	[AU]	Minimum heliocentric distance of the NEO during mission
D_{max}	[AU]	Maximum heliocentric distance of the NEO during mission
t_{PERIOD}	[hours]	Period of NEO rotation about its axis
C_C	[%wt]	Effective concentration of elemental carbon in ore of NEO
C_H	[%wt]	Effective concentration of elemental hydrogen in ore of NEO
C_S	[%wt]	Effective concentration of elemental sulfur in ore of NEO

Note that this list was not developed in isolation, being expanded as the need arose from development of the sizing code. It is believed that the list of input parameter satisfies 5Q, as stated in conjecture 5 below.

Conjecture 5 (5C)

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

The nominal values for the input parameters are also grouped together in Table 5-2 for reference. Recall that JAXA Hayabusa 2 is sampling Ryugu and NASA OSIRIS-REx is sampling Bennu, with both being C-type NEO. Note that round-trip Δv was used since return Δv was not found from an authoritative source, with a time on station of 100 days and a sample payload of one metric ton arbitrarily selected.

Table 5-2: Nominal values for input parameters

Parameter	*Units*	*Ryugu*	*Bennu*	*Source*
PROP_TYPE		Hydrolox	Hydrolox	Table 4-8
Δv_{RT}	m/s	4646	5087	[76]
t_{STAY}	days	100	100	
m_{SAMP}	kg	2000	2000	
D_{min}	AU	0.9633	0.8969	[167]
D_{max}	AU	1.416	1.356	[167]
t_{PERIOD}	h	7.633	4.296	[167]
C_C	%wt	3.22%	3.22%	[151]
C_H	%wt	2.02%	2.02%	[151]
C_S	%wt	5.25%	5.25%	[151]

5.2 Sizing Code Overview

With the necessary input parameters determined, a sizing code to utilize them can be developed. This sizing code is intended to provide enough functionality to size the concepts selected in § 4.5 for each propellant type. This methodology then works backwards from the return flight to size each part of the ISRU SoS in turn, as shown in the design structure matrix in Figure 5-11. This design structure matrix rearranges the systems identified in Figure 4-3 to minimize feed-backward iterations below the diagonal to reduce runtime. The procedure taken to size systems can be thought of as conducting the mission in reverse order, with the latter goals sizing the mass and energy use flows that subsequent systems need for their sizing routines. Please note that this analysis assumes the payload being returned is raw regolith from the NEO, with propellant for the return trip produced by ISPP SoS in line with the selected mission.

For each code module, a concise description will be provided in the subsequent subsections. These will describe the purpose of code module, a general description of the computations preformed, and key assumptions made. Also, a small library of shared rubberized component sizing routines was created for shared components like pressure vessels. Additional insights such as verification studies and list of optional inputs for each module with default values and corresponding sources are available in Appendix C.

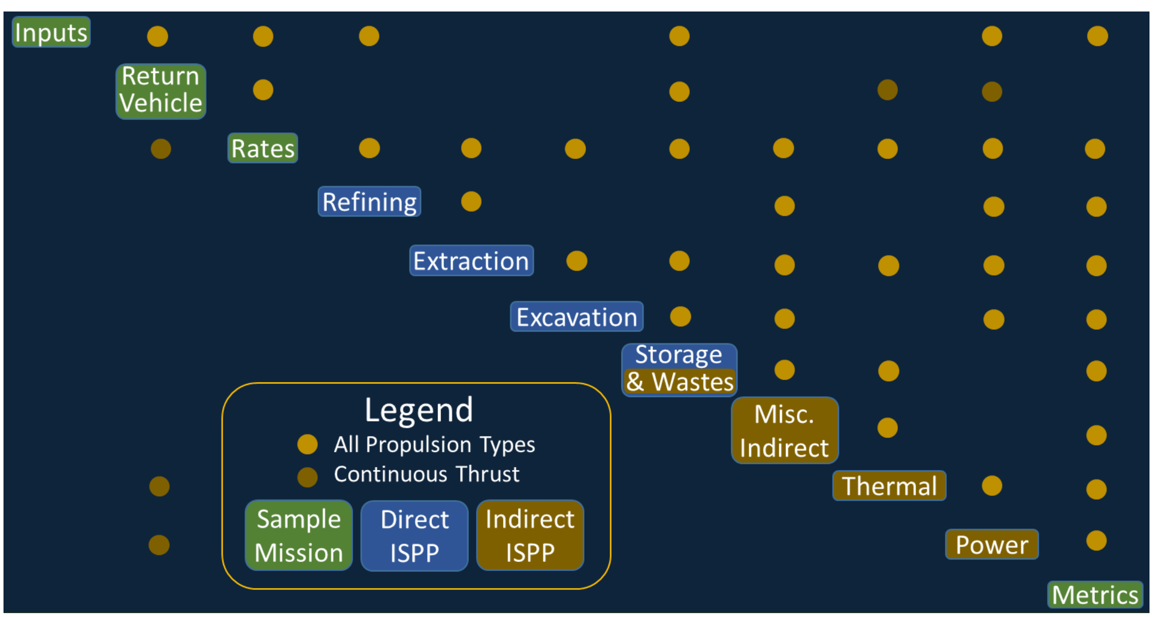


Figure 5-11: Design structure matrix for modules of sizing code. Note feed-forward interactions are above the diagonal, with most iterative loops within modules.

5.2.1 Propellant to Return

The first step to sizing an In-Situ *Propellant* Production (ISPP) SoS is to determine the amount of propellant required. This is accomplished using the return vehicle class, which computes the propellant mass required to complete the return trip from the NEO to LEO. An implementation of Tsiolkovsky's Rocket Equation (1) along with estimation of the bare dry mass by iterating upon sizing relations of an orbital launch vehicle provided by Akin [177]. Additional details on return vehicle sizing are provided in § C.3.3. Though an in-space transfer stage is sized, its mass is not included in that of the mass deployed to the NEO for the purposes of the mass payback ratio calculation. This is due to a strong possibility that the same in-space transfer stage used to send ISPP equipment to the NEO will be refueled using the same ISPP equipment in order to return to LEO.

Table 5-3: Return vehicle parameter default values for each propellant choice

Propellant	I_{sp}[s]	m_{eng}[kg]	P_{eng}[W]	η_{eng}[%]	*Comparable Engine*	*Sources*
Hydrogen	3000 s	500 kg	100 kW	70% eff.	Ad Astra VASIMR VF-200	[178], [179]
Water (Steam)	270 s	118 kg	480 kW	50% eff.	TransAstra Omnivore, Operating at 1850 K	[89], [165], [180]
Hydrolox	460.1 s	230 kg	mix 5.7		Aerojet Rocketdyne RL10C-3	[181]
Methalox	362 s	250 kg	mix 3.4		Avio Vega M10	[182]

In order to get the demanded propellant mass, several restrictive assumptions about the mission architecture must be made. First and foremost, a single stage rocket consuming ISPP produced propellants is assumed for the return trip. This is done to match the selected mission, where only simple molecules that can be synthesized from NEO ore in decent quantities can be used as propellant. The built in default values depend upon the propellant type selected, as given in Table 5-3. Specific engine designs were referenced instead of scaling dynamically to simplify the code and avoid sensitive content. The zirconia variant of the TransAstra Omnivore with quoted $I_{sp} = 270$ s is used for steam, with more detail on this decision in § C.3.2 and accompanying Figure C-1 [165]. Optical power was reverse engineered assuming 1 AU solar distance. These default values, and most others, can be overridden by providing secondary inputs when the module is called.

Secondly two impulsive burns are implicitly assumed, one for NEO departure and another for capture in LEO. No efforts were made to adjust continuous Δv relative to impulsive Δv for differing transfer orbits since there did not appear to be a discernable trend in the literature. In addition, zero boil off is assumed for simplicity on a coast period that may take up to several months. Tank volume sizing assumes spherical tanks of cryogenic liquid propellants, with the exception of subcooled ice for steam propellant. Note that these deficiencies can be somewhat overcome by using the 'oversize' factor to force the ISPP SoS to produce more propellant than the return vehicle demands. Increasing the unusable propellant fraction of the return vehicle may also suffice. Though these assumptions implicate some fairly severe limitations on the return vehicle sizing, it achieves the goal of a means to compute propellant masses given Δv and a propellant type.

5.2.2 Rate Adjustment

After the required propellant mass to return is computed in the return vehicle module, this and other inputs to the sizing code are tweaked in the rates module. These tweaks are best thought of as mapping the more general inputs into more relevant quantities for the sizing code to use. Doing so helped reduce repeat calculations, and allowed the user to provide higher-level inputs into the sizing code that are more relevant in conceptual design.

The mapping of inputs also has a second purpose, in permitting the use of adjustment factors to account for some externalized design or mission decisions. First, time on station is converted into the useful time for propellant production (t_{PROD}) [s] (aka `t_s`), by accounting for the useable time fraction (default = 75%) as well as light and dark operating fractions (both defaults = 100%). This is done to note that other activities occur in the vicinity of the NEO, such as setting up and checking out systems before operational use. By converting static quantities (mass and energy) into rates (mass flows and power), time on station is linked to the overall system sizing.

Second, fuel and oxidizer masses are adjusted up to stochiometric levels $(mix_{methalox} = 3.99,\ mix_{hydrolox} = 7.94)$ based upon the limiting reactant, then multiplied by an oversizing factor (default = `redundancy`; its default is 1). Redundancy increases the number of instances of equipment, and divides production between them. These adjustments account for excess propellant (esp. oxidizer) produced, and allow adding margin on mass flows for other effects like propellant boil-off.

Third, heliocentric distance is mapped to solar irradiance and average ambient temperature. Values are computed for both the minimum and maximum heliocentric distances during the mission, for which NEO aphelion and perihelion respectively make good guesses absent more detailed information on mission design. The solar irradiance flux is computed using an inverse square law to scale a solar constant value of $1360.8\ \mathrm{W/m^2}$ at 1 AU [166], [183]. The radiative equilibrium temperature is then computed using equation 22-19 from *New SMAD*, adapted to include a beam parameter and assuming a spherical NEO [137]. This links heliocentric distance to thermal design aspects.

5.2.3 Refinery Sizing

After the primary inputs are mapped and the demanded propellant mass adjusted, the next step is to size the systems that produce propellant. The refine module is tasked with computing the mass of plant required to convert resources (water and carbon dioxide) into consumables (propellant). Note that storage of the propellant is put off until latter since boil-off is not explicitly considered in this analysis, and the return vehicle may double as the holding tanks for the propellant produced.

To refine propellant, the selected equipment sized, or lack thereof, depends greatly upon the propellant type selected. For methalox, a Sabatier reactor is sized followed by a proton exchange membrane (PEM) electrolyzer. For hydrolox, only a PEM electrolyzer is sized. For steam, nothing is sized. It is assumed here that extremely pure carbon dioxide and deionized water are provided from the extraction step; otherwise the PEM electrolyzer would foul up in short order and cease operating. The sizing codes for the Sabatier reactor and the PEM electrolyzer are adapted from MIT's HabNet as described in the theses of Schrenk and Do [93], [113]. These models have been implemented as fixed value multiple instance systems with some adaptive components in line with the original designs that Schrenk cited. The main differences are the implementation of a more advanced pressure vessel sizing routine, energy use computed, and redundancy modifiers to set minimum instances. Headers were also added to convert mass flow rates into molar rates and enforce stochiometric reactions, as well as footers to tweak mass flow rates to account for the production of water by the Sabatier reactor if it is present. The quantity of resources required to be extracted from the propellant demanded is computed by the headers. Lastly, the mass and power of the subsystems present is summed to obtain a subtotal.

5.2.4 *Extraction Sizing*

After the amount of resources required (water and carbon dioxide) are computed, the next step is to compute the amount of NEO ore required to obtain those resources. The extraction class sizes all the subsystems required for this, most notably extracting substances from the NEO ore and purifying those substances into an useable form. To extract the substances, a thermal vacuum chamber to evolve volatile gasses has been selected. For beneficiation a series of adsorption units then absorption units have been selected have been selected to separate the gas streams. After all the extraction subsystems are sized, the mass, power, heating, and cooling terms are summed to obtain a subtotal.

To begin, the quantity of ore required is determined from the desired quantity of resources to be extracted. There were three main questions driving extraction model development: What is the composition of a C-type NEO? Which gases are evolved? How can the extraction process be parameterized? Due to the differing minerologies present, and concerns about changes due to atmospheric reentry, and spectroscopy data available elemental breakdowns were selected to be used to parameterize composition throughout this work. The 'CI' simulant developed by Deep Space Industries and the University of Central Florida is based upon the composition of the Orgueil meteorite, which includes 3.22%wt C, 2.02%wt H, and 5.25%wt S [151]. These three elements were chosen to be tracked since it was noted that water, carbon dioxide, and sulfur dioxide accounted for over 99.5% of the gasses evolved when heating CI simulant from 15 °C to 1000 °C as per Figure 5-10 [50], [176]. All other trace volatiles are neglected to simplify the analysis. By comparing the computed evolved quantities for these three molecules with the best case scenario as described in § C.6.2, values for the thermal extraction process efficiencies were computed. These default values are 37.5% of max H_2O per %wt H in ore, 17.6% of max CO_2 per %wt C in ore, and 6.71% of max SO_2 per %wt S in ore respectively. Combined with elemental composition values, a mass ratio of resource yield per NEO ore is computed. The water and carbon dioxide yield per ore mass ratios are then multiplied by the masses of water and carbon dioxide demanded respectively, with the larger of the two values becoming the quantity of ore demanded by the extraction module.

With the mass of evolved volatile gasses computed, the next step is to size the equipment required to perform this feat. From a search of terrestrial analogs resulted in the selection of a vacuum furnace to do this [184]. The furnace sized internal volume is computed using NEO ore density (default = regolith value of $1190\ \mathrm{kg/m^3}$ from Bennu and Ryugu), and an estimated takt time for the process [185], [186]. Both the latent heat of sublimation for volatiles (~1/3 heating demand) and specific heat capacity at constant pressure for both volatiles and regolith (~2/3 heating demand) were used along with the batch size and takt time to compute the heating demand for the vacuum furnace [187]–[190]. An auger was also sized to move ore into and tailings out of the vacuum furnace.

The volatiles exiting the vacuum furnace were then cooled using their specific heat capacities to enter the beneficiation subsystem to separate the gas streams. Note that currently only the heating and cooling requirements for the pressure swing adsorption sorbent beds and filters is sized, not their masses. This last step is important, since sulfuric acid formation is suspected at the relatively high temperatures used in the vacuum furnace. In addition, the PEM electrolyzers used in the refining module are noted to have exceptionally low impurity tolerances for dissolved ions.

5.2.5 Excavation Sizing

With the amount of NEO ore computed, the next step is to compute the amount of regolith to be excavated. The excavation module handles this by combining information on the samples to be returned and extraction process results, and also sizes the corresponding subsystems to handle the regolith. Though regolith is assumed to be identical to ore by default, functionality is included to adjust geological and processing inputs. When combined with the chemical composition inputs in the extraction module, trade studies between ore grade versus overburden removal are enabled. This approach was selected to permit modeling of ore and overburden of different mineralogy.

To compute the amount of bulk NEO regolith to be excavated, it is important to consider both the demanded quantity of ore and the type of samples requested. Ore is assumed identical to regolith unless otherwise specified, through providing an overburden proportion (default = 0%), density (default = $1190\ \mathrm{kg/m^3}$), porosity (default = 50%), and/or cutting energy (default = $2.54 * 10^8\ \mathrm{J/m^3}$) as secondary input(s) [185], [186]. Density is used to find volumes, accounting for compaction if present (default = 0%). Cutting energy is based upon the volume of kerf cut, and was computed from HoneyBee Robotics corer test data [191]. Overburden is excavated material that does not undergo extraction, with samples of both ore (default = 50% of 2000 kg) and overburden assumed to be of interest to be returned to LEO. Tailing samples may also be of interest, and are lumped in with overburden in this model.

Corers were selected for extraction to permit the widest range of sampling opportunities, reduce sample alteration during collection, and minimize debris released from cutting. Corers remove the regolith and augers transport it for extraction, with robotic arms anticipated to reposition the corers but not sized at the present time. The corer used was modeled using values from HoneyBee Robotic's The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) subsystem in their Planetary Volatiles Extractor (PVEx) system [147], [148]. Kerf from the cut is included in the excavated volume for the ore and overburden, but not for the samples. The quantity of corers required is computed by ascertaining the number of cores drilled per corer and the total number of cores required. The corer power is computed using the aggregate kerf volume and its cutting energy of both the ore and overburden.

5.2.6 Storage Sizing

The storage module computes mass of containers for byproducts and consumables. It is assumed that all wastes are stored, in order to reduce the probability of debris hitting equipment or clinging to surfaces like solar panels or radiators. If a mass is not passed into the class or has zero mass to store, a pressure vessel will not be sized. Note that boil-off is not explicitly considered in this analysis, though may be specified using the oversize factor in the rates module. The code is setup size a rubberized pressure vessels based upon the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC) for each mass input. Tanks are sized to hold a pressure of 1 atmosphere (101,325 Pa), length to diameter ration of 4, and have ellipsoid ends by default. All volatiles are liquified or sublimated prior to storage, causing a cooling load to be introduced. For overburden and tailings, thin tank is sized by decreasing the pressure of the tank walls to 10,000 Pa, with neither a heating nor cooling load considered.

5.2.7 Miscellaneous Sizing

After the storage module is sized, the main sequence of systems in direct contact with the mass flows of processing has been established. There are still a few pertinent systems that need to be sized before energy use demands are met though. The remaining functionality not in either of these two categories contains most of the functions inherent in prospecting, material handling, avionics, and structures. The reason these elements can be lumped together is that they have limited interdependence upon each other, so the order in which these systems are sized does not matter quite as much. For this reason, they are limped together under the label 'miscellaneous'.

Due to the label of being miscellaneous systems they admittedly had a lower priority in the development queue. Some functions were incorporated into the other modules in the process. Augers for granular solid transport and extra corers present to aid anchoring sized as a part of excavation are both examples of this. Others functions ended up being selected but not yet sized due to the amphibious scope of the thesis, as shown in Table 5-5. Communications subsystems are one such example of part of the avionics system that did not end up being sized. Recognizing the absent subsystem masses as well as the novelty of the designs, the decision was made to introduce fairly high fairly high values for system mass contingencies (30%) and overall SoS mass margin (30%) by default to compensate for the missing sizing routines in the code. The net observed effect was nearly doubling the overall ISPP plant mass which should hopefully cover missing system masses, although at the cost of slightly reduced accuracy in the modeling of trends within the design space. This trade is not ideal, but was deemed the best alternative to deliver the majority of the requested capabilities.

5.2.8 Thermal Management Sizing

The thermal module computes mass of thermal management system to keep SoS in a comfortable temperature rage. Data on assumed ambient temperatures for the NEO is taken from the rates module, along with the strength of incident solar radiation at the minimum and maximum heliocentric distances. Note that due to the varying heliocentric distance, sizing power and thermal management systems directly is being pursued instead of an equivalent system mass approach.

Heating systems are sized when the SoS is assumed to be at the maximum heliocentric distance expected during the mission. Industrial grade infrared lamps are used to provide primary heat for extraction. Not all radiative heating makes it to the target, so a cooling load is also introduced. Cooling systems are sized when the SoS is assumed to be at the minimum heliocentric distance expected during the mission. Radiators are scaled based upon area to meet the cooling load, based upon radiative equilibrium calculations including the black body radiation given off the NEO.

5.2.9 Power Management Sizing

The power class computes the mass of the power management system. Data on the strength of incident solar radiation at the maximum heliocentric distance assumed during the mission is taken from the rates module. Data on the rotation period of the NEO is used to determine the length of diurnal cycles. Since systems attached to the surface of the NEO (small spacecraft sent to large diameter NEO) were assumed, the photovoltaic panels for power were paired with lithium ion batteries for energy storage.

Solar panels were sized to generate enough electrical energy for a full diurnal cycle during the sunlit portion of it, accounting for battery charge and discharge inefficiencies. Solar panels were scaled by area to the sufficient size. Integer multiples of COTS Lithium ion battery cells were then sized to power the SoS throughout the night, with constant power load at the rated value assumed. Note that the default batteries are noted to be qualified for 233 K (-40 °C) to 358 (85 °C), and the ambient temperature for Ryugu is expected to be in the range 277 K to 336 K [192], [193]. Thus, heaters were not included.

5.2.10 Executing Cases

To size a concept a case integrator module is used. This code handles all data transfer between modules, implementing the design structure matrix shown in Figure 5-11. The validity of required inputs is checked, as well as output metrics computed at this point.

Table 5-4: Degree of sizing implementation for selected concepts and a tweaked TransAstra HoneyBee. Note that reasonable and limited are both considered sized.

Concept Name	Propellant	Reasonable	Limited	None	Sized
HoneyBee {Tweaked}	*Steam - Optical*	9	6	19	44%
Concept 'S'	*Steam - Electrical*	14	8	15	59%
Concept 'H'	*Hydrogen*	16	8	15	62%
Concept 'HO'	*Hydrolox*	17	8	15	63%
Concept 'MO'	*Methalox*	18	8	15	63%
	Proportion in Designation:	39%	20%	41%	59%

Unfortunately, not all of the selected functions were able to be implemented within the sizing code as part of this thesis. Table 5-5 shows the selected concepts from Table 4-7, with the degree of sizing implementation shaded. A summary of the proportion of each selected concept sized is in Table 5-4. Here, a morphological option was deemed to be reasonably sized for pre-conceptual design if all major aspects were represented in some way. A limited sizing implementation has some but not all of the major aspects represented,

Table 5-5: Selected concepts with degree of sizing implementation shaded

Task	Group	Category	HoneyBee {tweaked} Steam - Optical	Concept 'S' Steam - Electric	Concept 'H' Hydrogen	Concept 'HO' Hydrolox	Concept 'MO' Methalox
		Implementaiton of Selected Options					
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	Visible Light	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	Filtration	Filtration	Filtration	Filtration
	Extraction	Heating [Primary]	Focused Sunlight	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)	Light (lamp/laser)
		Beneficiation	N/A	Centrifugal (Density)	Centrifugal (Density)	Centrifugal (Density)	Centrifugal (Density)
		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, Blower,	Shaft Work (Pump, Blower,	Shaft Work (Pump, Blower,	Shaft Work (Pump, Blower,
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
	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
		Beam Transmission	Mirrors	N/A	N/A	N/A	N/A
	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

Legend:
Reasonable
Limited
Not Sized
N/A

Italics are 'best guess' on design intent or was selectively implemented in some places but not others. If a functional niche was considered reasonable or limited, some sizing was said to have been conducted.

The case integrator is also paired with a batch handler to size multiple concepts at once. This is done by reading in a comma separated value (CSV) file into the sizing code, and saving all results to another CSV file. Pandas data frames are used to sort the output columns to have the DoE inputs followed by output metrics, then the rest alphabetically. Note that the code is structured such that as many arbitrarily named inputs can be passed into the sizing code as part of the DoE through python's keyword arguments dictionaries. This functionality is intended to be used to permit overriding default values in the sizing code to permit sensitivity studies, or for future development of additional modules. SoS level optional arguments such as mass margin (default 30%) are also dealt with at this stage. Note that the DoE runner will alert the user through the console if an input variable is unused. Multiple output modes are possible for diagnostic purposes, including a dump of all variables used. By default, most variables are output though duplicates between classes are overwritten.

5.3 Output Metrics

With routines to size each of the selected systems described, the final step is to formulate output metrics to quantify the performance of the design. This sizing code has focused on ascertaining the mass of processing equipment required, as well as the energy needed to run the equipment. Sized SoS quantities, ratio analysis, and system metrics were each considered. Concise descriptions of these three groups of and their corresponding output are thus described in the following subsections.

5.3.1 Sized Quantities

Sized quantities include cumulative SoS mass, power, and heat flows, along with the total mass of matter processed at different stages in the design. Please note that as the regolith is processed into propellant matter is periodically removed, in the relationships represented in equation (2). Definitions for mass terms can be found in § 4.2.

$$\begin{array}{ccccccccc} m_{REG} & \geq m_{ORE} & > m_{VOLS} & > m_{CON} & > m_{PROP} & ; & < m_{PROD} \\ & (-m_{OVER}) & (-m_{TAIL}) & (-m_{BYP}) & (-m_{EX}) & & (+m_{PAY}) \end{array} \tag{2}$$

m_{REG} [kg] Mass of bulk regolith excavated from the NEO

m_{ORE} [kg] Mass of ore excavated from the NEO

m_{OVER} [kg] Mass of overburden excavated; $m_{OVER} \equiv m_{REG} - m_{ORE}$

m_{VOLS} [kg] Mass of volatiles extracted from the ore; (CO_2, H_2O, and SO_2)

m_{TAIL} [kg] Mass of tailings from ore; $m_{TAIL} \equiv m_{ORE} - m_{VOLS}$

m_{CON} [kg] Mass of consumeables produced; (CH_4, H_2, H_2O, and/or O_2)

m_{BYP} [kg] Mass of byproducts produced; $m_{BYP} \equiv m_{VOLS} - m_{CON}$

m_{PROP} [kg] Mass of the propellant demanded; $m_{PROP} \equiv m_{fuel} + m_{ox}$

m_{EX} [kg] Mass consumeables in excess of demand; $m_{EX} \equiv m_{CON} - m_{PROP}$

m_{PROD} [kg] Mass of produced resources; $m_{PROD} = m_{PROP} + m_{PAY}$

These are used throughout the sizing code as intermediate values, with the following overall mass, power, and heat flows computed towards the end of code execution.

m_{ISPP} [kg] Total mass of the ISPP SoS deployed to the NEO

P_{ISPP} [We] Total maximum electrical power load of the ISPP SoS

$Q_{C,ISPP}$ [Wt] Total maximum cooling load of the ISPP SoS

$Q_{H,ISPP}$ [Wt] Total maximum heating load of the ISPP SoS

5.3.2 Ratio Analysis

With the sized quantities, several ratios of interest to characterize the overall SoS can be computed. Of these, the Mass Payback Ratio (MPR) is the primary metric of interest, and the metric most commonly used in other sources if any performance metric is provided. Specific Energy Intensity (SEI) is also of interest, comparing the rate at which electrical and thermal energy is utilized to the effective average propellant production rate. Two additional metrics are introduced to evaluate how effective the SoS is at processing space resources from the bulk regolith and the volatiles that it evolves.

MPR	$[\mathrm{n.d.}]$ Overall mass payback ratio;	$MPR = m_{PROD}/m_{ISPP}$
MPR_{PROP}	$[\mathrm{n.d.}]$ Propellant mass payback ratio;	$MPR_{PROP} = m_{PROP}/m_{ISPP}$
f	$[1/\mathrm{day}]$ Overall mass throughput for propellant;	$f = MPR_{PROP}/\mathrm{t_{PROD}}$
f_{REG}	$[1/\mathrm{day}]$ Regolith processing throughput;	$f_{REG} = m_{REG}/(m_{ISPP} * \mathrm{t_{PROD}})$
SEI	$[\mathrm{J/kg}]$ Specific Energy Intensity of propellant produced, a ratio of rates: power to mass flow;	$SEI = \left(P_{ISPP} + Q_{C,ISPP} + Q_{H,ISPP}\right)/\dot{m}_{PROP}$
$\dot{m}_{PROP}$	$[\mathrm{kg}/s]$ Effective average propellant production rate, adjusted for useful time and if plant oversized;	$\dot{m}_{PROP} = Oversize * m_{PROP}/\mathrm{t_{PROD}}$
$UseReg$	[%wt] Proportion of regolith used in products;	m_{PROD}/m_{REG}
$UseVols$	[%wt] Proportion of evolved volatiles making propellant;	m_{PROP}/m_{VOLS}

5.3.3 System Metrics

In addition to evaluating the performance of the SoS as a whole, that ability to evaluate relative resource use between systems in a concept is of interest. Three types of relative comparisons are undertaken: mass fractions, power use fractions, and process return. Mass fractions allocate the total mass of all processing equipment mass by taking the mass of equipment for each system and dividing it by the total. Energy use fractions work similarly, totalling the total magnitude of demand for electrical power, heating, and cooling across all systems and dividing it by the corresponding value for each system.

(zeta) ζ [%wt] Mass fraction; $\zeta_{EXC} = m_{EXC}/m_{ISPP}$

(xi) ξ [%en] Energy use fraction; $\xi_{EXC} = \frac{P_{EXC}+Q_{EXC}+Q_{EXC}}{P_{ISPP}+Q_{C,ISPP}+Q_{H,ISPP}}$

Process Return (PR) [n. d.] compares the mass of matter processed by a direct ISRU system to the mass or equipment required to do so. This makes PR a system level analog to MPR, with its time-specific form also being mass throughput (f) [1/day] for a system.

f_{EXC} [1/day] Excavation mass throughput; $f_{EXC} \equiv m_{ORE}/(m_{EXC} * \mathrm{t_{PROD}})$

f_{EXT} [1/day] Extraction mass throughput; $f_{EXT} \equiv m_{VOLS}/(m_{EXT} * \mathrm{t_{PROD}})$

f_{REF} [1/day] Refining mass throughput; $f_{REF} \equiv m_{PROP}/(m_{REF} * \mathrm{t_{PROD}})$

f_{STO} [1/day] Storage mass throughput; eqaution here assumes wastes stored
$f_{STO} = (m_{PAY} + m_{VOLS} + m_{OVER} + m_{TAIL})/(m_{STO} * \mathrm{t_{PROD}})$

In addition, power mass penalties [kg/kW] were formulated, comparing the maximum rate of energy demand to the sized mass of the equipment to fulfill the respective function [108]. For power, the sized mass of solar panels and lithium ion batteries is divided by the maximum power demanded. For heating, the mass of industrial heating lamps is compared to the maximum heating power demanded, For cooling, the mass of radiators is divided by the maximum cooling power demanded. In this way, the performance of the overall SoS and the systems within are quantified for comparison.

PMP_P [kg/kW] Electrical power mass penalty; $PMP_P = m_{Power}/\mathrm{P_{ISPP}}$

PMP_H [kg/kW] Heating power mass penalty; $PMP_H = \frac{m_{Lamp}(1+CONT_{Therm})}{\mathrm{Q_{H,ISPP}}}$

PMP_C [kg/kW] Cooling power mass penalty; $PMP_C = \frac{m_{Rad}(1+CONT_{Therm})}{\mathrm{Q_{C,ISPP}}}$

CHAPTER 6. CASE STUDIES

Now that a sizing code has been developed, the last piece of the puzzle is in place for case studies to be conducted to answer the trade study posed in research question 5 (Q5) in § 3.6 on case studies considered, with the hypothesis 5 reproduced below. This statement is based upon the complexity to produce each propellant, and space resource availability.

Hypothesis 5 (H5)
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.

This trade study is being conducted to differentiate steam monopropellant, hydrogen monopropellant, hydrogen-oxygen bipropellant (hydrolox), and methane-oxygen bipropellant (methalox). Corresponding concepts were qualitatively down-selected from the morphological options available in § 4.5 on the selected baseline concept. Experiments 1 and 2 are intended to address how quantitative aspects affect the sizing of these concepts to discern trends. The former is intended to address how NEO orbital characteristics affect the sized result. The latter is intended to address NEO composition as well. For each experiment a Design of Experiments (DoE) is created to explore the design space of relevant parameter values. Important results are presented herein, with a focus on the relative plant sizing of each propellant type. Relative system sizing is briefly discussed, with further treatment of appropriate system metrics from § 5.3.3 in Appendix C.

6.1 Experiment 1: NEO Orbital Characteristics

From conducting background research for sizing, it was determined that NEO orbital characteristics can be described in the context of the selected mission by describing both mission parameters and solar radiation effects. Of these input parameters, it was hypothesized that the change in velocity required to return (Δv_{RT} [km/s]) would have the largest influence upon design sizing. This is restated in hypothesis 5.1, reproduced below.

Hypothesis 5.1 (H5.1)

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.

6.1.1 Design Ranges for Input Parameters

266 Cases in fast, flexible space filling design were generated, with eight additional nominal points (2 NEO by 4 propellants). Note this includes 66 cases which were tacked on latter to add the hydrogen propellant type, and the constraint $D_{min} \leq D_{max}$. Nominal values in Table 6-1 are for Ryugu, with Bennu values also considered in the 8 additional nominal cases (two asteroids by four propellant types). NEO composition was held constant at Exolith Lab CI simulant values (3.22%wt carbon, 2.02%wt hydrogen, 5.25%wt sulfur), along with a metric ton of samples (2,000 kg) to simplify comparisons [151].

Table 6-1: Ranges and nominal values used to generate DoE for experiment 1

Variable	*Units*	*Min.*	*Nom.*	*Max.*	*Source*
Δv_{RT}	m/s	500	4,646	8,000	[76], [164]
t_{STAY}	days	30	100	365	[164]
D_{min}	AU	0.75	0.9633	1.2	[164], [167]
D_{max}	AU	0.85	1.4159	1.45	[164], [167]
t_{PERIOD}	hours	2.5	7.6326	24	[167], [169]
$PROP\_TYPE$		Steam	Hydrolox	Methalox	Hydrogen

6.1.2 Comparison of Sized Systems

Before analyzing the performance of concepts in experiment 1, it is worth examining the relative sizing of constituent systems. It is informative to look at the expected values for each propellant type of the mass fractions (Figure 6-1) and energy use fractions (Figure 6-2) to gain insight into how the choice of propellant type influences plant sizing.

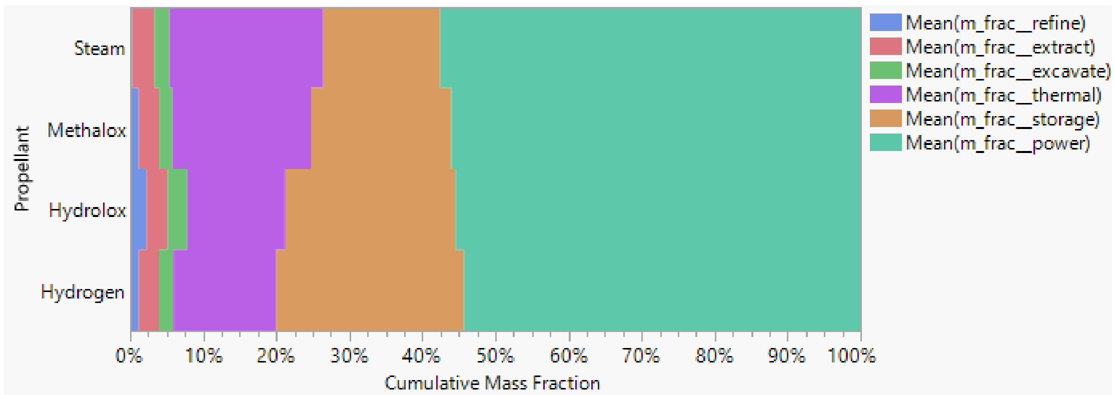


Figure 6-1: Cumulative mass fractions by propellant type for experiment 1

The electrical power system appears to consistently have the largest mass fraction on average, followed by storage or thermal depending upon the propellant type. Interestingly, the storage mass fraction (wastes included) contribution appears to follow the ordering of specific impulse between prop. Excavation and extraction appear invariant to prop. choice.

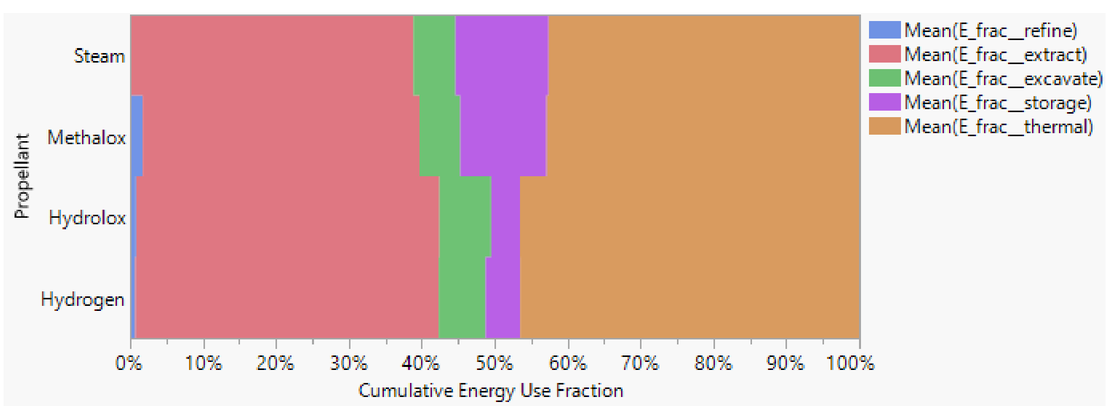


Figure 6-2: Cumulative energy use fractions by propellant type for experiment 1

Looking at the energy use fractions in Figure 6-2, extraction and thermal systems account for the vast majority of energy use. Note that the majority of thermal energy demand is currently from transformations between types of energy (e.g. extraction heat lamps to electrical power and cooling demand), and the energy use fraction distributions for extraction and thermal systems closely mirror each other (Figure C-7 vs. Figure C-12).

6.1.3 Relative Performance

To gauge the performance of sized NEO ISPP concepts, the plant mass and mass payback ratio are examined, being the primary 'cost' and 'benefit' that are usually considered for ISRU. Figure 6-3 shows the mass payback ratio for each propellant computed two different ways. The right-hand bar only considered the demanded propellant quantity, while the left-hand bar also admits the samples returned as a resource due to cross-functionality of extraction equipment. Hydrolox and steam fair better than methalox

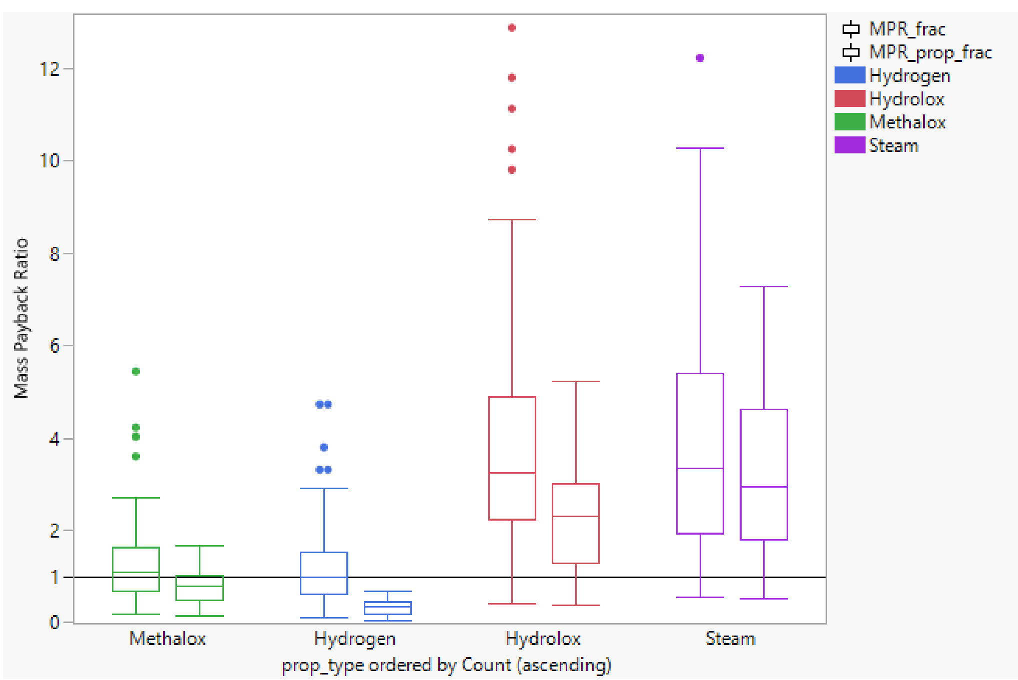


Figure 6-3: Mass Payback Ratios (with sample, propellant only) vs. propellant type

and hydrogen on average, though all propellant types have occurrences where the benefits do not exceed the costs ($MPR < 1$, black line). It is observed that steam has the highest median mass payback ratio in both cases, with hydrogen failing to provide significant payback unless the mass of samples is considered.

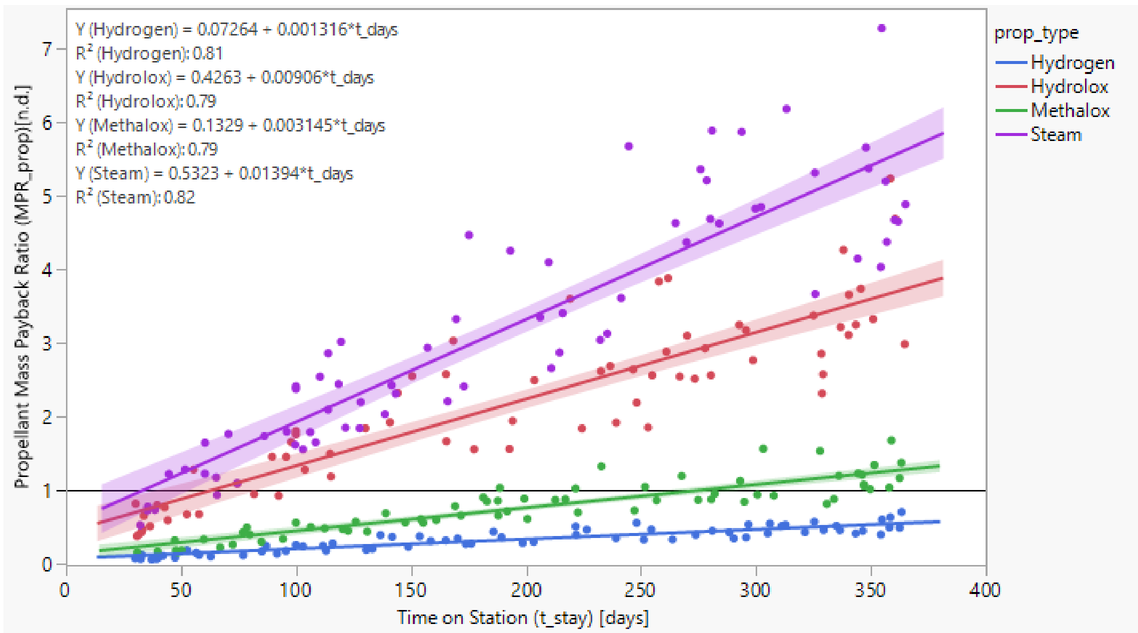


Figure 6-4: Propellant mass payback ratio vs. time on station by propellant type

It is also worth noting that the propellant mass payback ratio has reduced variability of the two MPR used, permitting the discernment of more meaningful relationships. Figure 6-4 shows the propellant mass payback ratio compared to the time on station at the NEO, with the resulting fits explaining at least 79% of the variability in the data for each propellant type. Steam tends to have the highest MPR, followed by hydrolox, methalox, then hydrogen. It is notable that the slope of each fit follows the same trend. All propellant types considered have have occurrences where the benefits do not exceed the costs ($MPR < 1$, black line) consistent with Figure 6-3, though the likelihood of such an occurrence decreases as the time on station is extended.

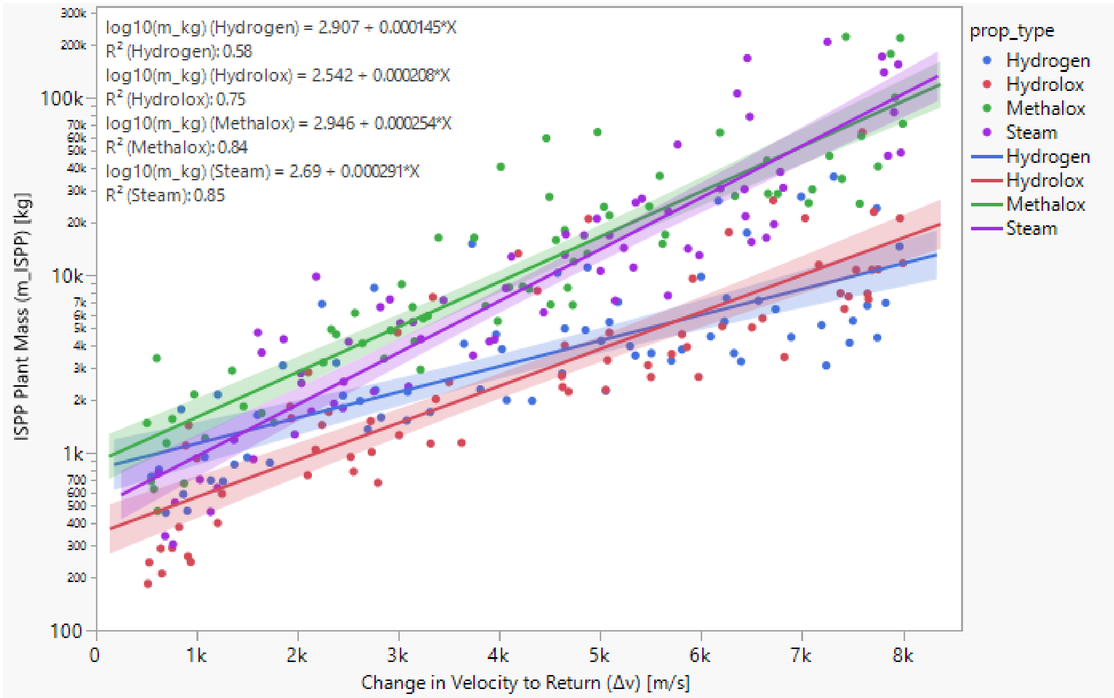


Figure 6-5: SoS plant mass versus return Δv by propellant type for experiment 1

Still, this look at MPRs does not tell the whole story. Figure 6-5 compares the sized plant mass on a logarithmic scale to the change in velocity for return (Δv). It is noted that sized plant masses tend to be on the order of metric tons to produce enough propellant to return a metric ton of samples (2000 kg) around the nominal $\Delta v \approx 4.6\ \text{km/s}$. There appear to be two groups of propellants by slope: hydrogen and hydrolox, as well as methalox and steam. These groupings do not follow the distinction between continuous and impulsive propellant types, though a decreased slope appears to be related to a higher specific impulse in some fashion. It is also quite interesting to note that steam tends to have a relatively more massive plant mass in Figure 6-5 despite tending to have the highest MPR_{PROP} on average in Figure 6-4. Similarly, hydrolox tends to have a lighter plant mass, the lightest for $\Delta v_{RT} \gtrsim 5.8\ \text{km/s}$, despite consistently having the lowest MPR_{PROP}. Hydrolox tends to the be lightest for low Δv, and has the second highest MPR_{PROP} of those considered.

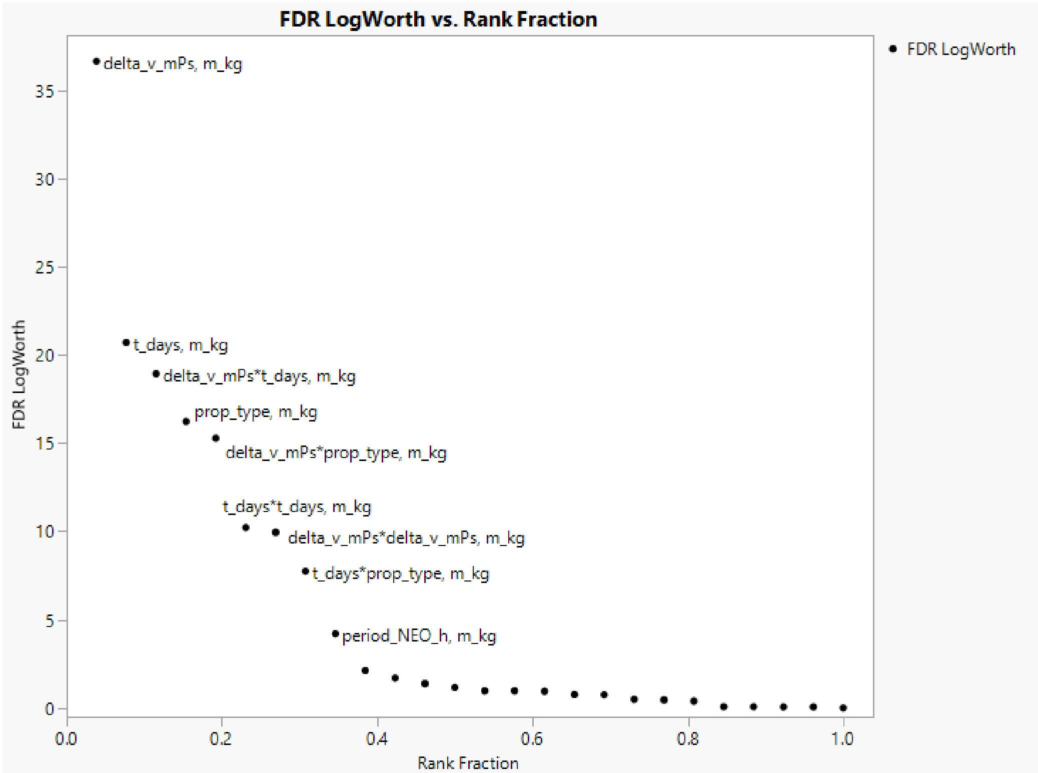


Figure 6-6: Main effects and cross terms for experiment 1 DoE characterized by the false discovery rate logarithmic worth for variation in plant mass.

Note that Δv is deemed to have a highly significant effect on the sized mass of the plant ($PValue \approx 8 * 10^{-39}$), higher than any other effect in Figure 6-6. Δv also accounted for $\geq$ 58% of the variability present in the sized plant mass of each propellant type, as shown by the regressions in Figure 6-5. Thus, it can be concluded that Δv does have the largest effect on the sized plant mass, and hypothesis 5.1 proven true in result 5.1.

Result 5.1 (R5.1)

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

6.2 Experiment 2: NEO Composition

With some interesting trends observed from conducting experiment 1, the time has come to augment the design space by also considering NEO composition. Since all four propellant types considered include a significant quantity of hydrogen and most include oxygen as well, the sizing of a ISPP plant is thought to heavily depend on the availability of water. This observation lead to hypothesis 5.2 below.

> **Hypothesis 5.2 (H5.2)**
>
> If sized ISPP plant mass sensitivity to NEO composition is analyzed, then the availability of water will have the greatest contribution to variability.

6.2.1 Design Ranges for Input Parameters

The availability of water is parameterized by the concentration of elemental hydrogen (C_H) [%wt] in the NEO ore, and the extraction efficiency (default = 37.5% for water). Enrichment of ore to the limits described in § 5.2.4 is justified through varying the proportion of overburden, or bulk NEO excavated that is not ore undergoing extraction.

Table 6-2: Ranges and nominal values used to generate DoE for experiment 2

Variable	*Units*	*Min.*	*Nom.*	*Max.*	*Source*
Δv_{RT}	m/s	500	4,646	8,000	[76], [164]
t_{STAY}	days	30	100	365	[164]
D_{min}	AU	0.75	0.9633	1.2	[164], [167]
D_{max}	AU	0.85	1.4159	1.45	[164], [167]
t_{PERIOD}	hours	2.5	7.6326	24	[167], [169]
$PROP\_TYPE$		Steam	Hydrolox	Methalox	Hydrogen
m_{PAY}	kg	100	2,000	10,000	
$OVERBURDEN$	%wt	0%	0%	90%	
C_C	%wt	0.50%	3.22%	15%	[151], § 5.2.4
C_H	%wt	0.50%	2.02%	5.49%	[151], § 5.2.4
C_S	%wt	0%	5.25%	10%	[151], § 5.2.4

13,334 Cases in fast, flexible space filling design were generated, with eight additional nominal points (2 NEO by 4 propellants). Note this includes 3,334 cases which were tacked on latter to add in hydrogen propellant. Nominal values in Table 6-2 are for Ryugu, with Bennu values also considered in the 8 additional nominal cases included. Constraint formulas were used to ensure $D_{min} \leq D_{max}$ and the mass of substances in the ore that could become volatiles (CO_2, H_2O, SO_2) could not exceed unity as per equation (3). Coefficients are the ratio of molar mass for the evolved gas to element parameterized.

$$3.664\ C_C + 17.87\ C_H + 2.061\ C_S \leq 100\%\text{wt} \tag{3}$$

6.2.2 Comparison of Sized Systems

Before analyzing the performance of concepts in experiment 2, it is worth going back and re-examining the relative sizing of constituent systems since new parameters are included and additional cases have been run. Trends in the expected value of the mass fractions across propellant types are similar (Figure 6-7 vs. Figure 6-1), except for slightly reduced power system and slightly increased excavation system mass fractions.

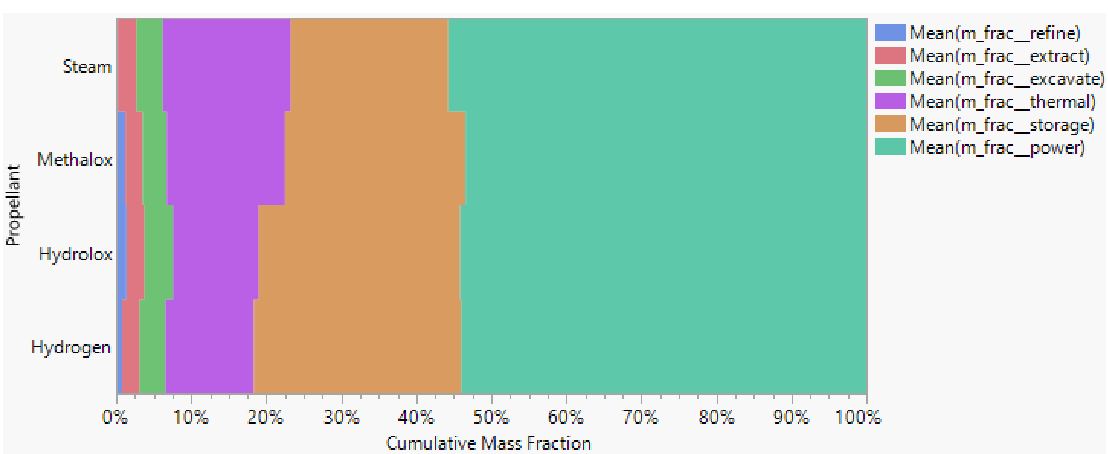


Figure 6-7: Cumulative mass fractions by propellant type for experiment 2

Excavation also has an increased energy use fraction on average (Figure 6-8 vs. Figure 6-2). Other relative system sizing by propellant appears to be largely unchanged from experiment 1. Distributions for values of the mass fraction, energy use fraction, mass throughput, and power mass penalty as appropriate for each system are in Appendix C.

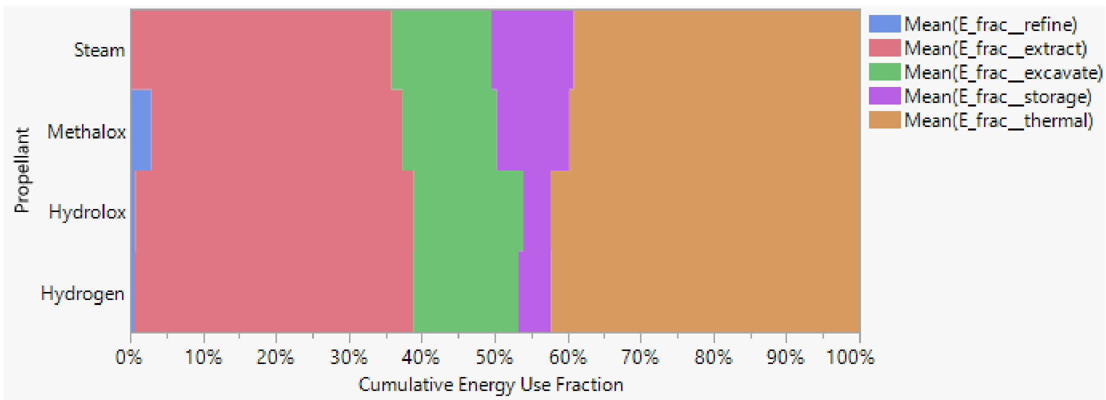


Figure 6-8: Cumulative energy use fractions by propellant type for experiment 2

Another group on metrics worth examining is the proportion of matter processed that does not go to waste, especially when varying composition. The useful regolith proportion tracks the effectiveness of the Direct ISRU systems to produce products from the bulk NEO regolith on a mass basis. The useful volatile proportion evaluates the proportion of evolved gasses (CO_2, H_2O, SO_2) that are processed into the demanded propellant quantity. When these two metrics are compared in Figure 6-9 on the right, both useful proportions tend to increase in tandem within a propellant type, with increases in the proportion of overburden leading to lower useful regolith proportions. Interestingly, these apparent overburden contours appear to be convex (increasing slope) for hydrogen, hydrolox, and steam, though concave for methalox. There also appears to be a maximum achievable useful volatile proportion for each propellant type.

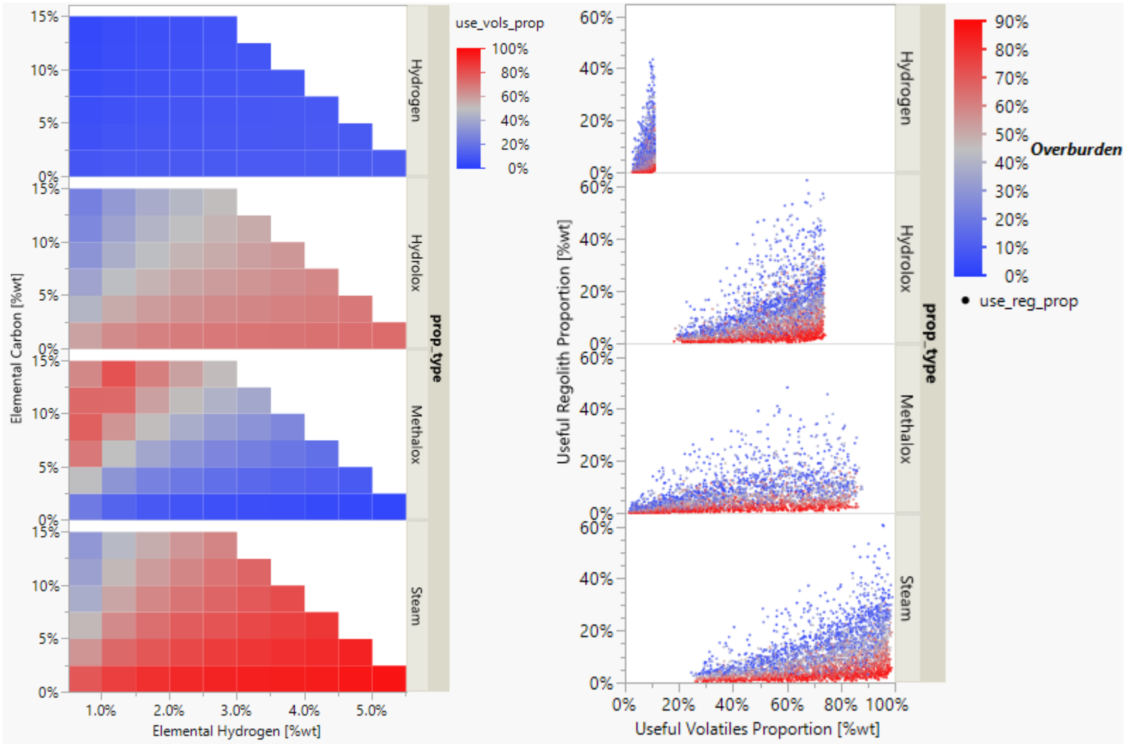


Figure 6-9: Useful volatile proportion vs. carbon and hydrogen by propellant type; Useful proportions of regoloth vs. volatiles and overburden fraction by propellant

By looking at the concentration of elemental hydrogen and carbon in the ore in Figure 6-9 to the left, insights can be had into what is driving the useful volatile proportion for each propellant type. Note that the upper right quadrant is infeasible due to constraint equation (3), which ensures that tracked elements in the NEO ore remain at or below 100%wt after accounting for the oxygen in their evolved gas oxide forms. Steam, hydrolox, and hydrogen all appear to have similar distributions here, though values on the left are scaled by the apparent maximum useful volatile proportion on the right. The useful volatile proportion for these propellants appears to primarily depend on hydrogen availability (used as water proxy), maxing out in the lower right corner.

Methalox is a different story altogether, with the carbon required flipping the contours to be better in the upper left. From the ranges considered, methalox appears to occupy a separate niche than the other propellants. The dividing line appears to be approximately 5:1 carbon to hydrogen by mass, with the best results for methalox around 10:1. The presence of too much carbon also appears to reduce the useful volatile proportion, unlike the other propellants for which the optimum appears to be pure ice. From these observations, it is deemed likely these complications restricting the usefulness of methalox stem from the additional requirement for a second feedstock, a source of carbon.

Result 5.2 (R5.2)
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.

6.2.3 *Relative Performance*

With these notes on the usefulness of different possible composition niches for propellant types, it is worth re-examining the MPRs and sized plant mass for each propellant type. The increased variability and longer tails from the distributions in Figure 6-10 (vs. Figure 6-3 and Figure 6-5) is expected from additional cases in experiment 2.

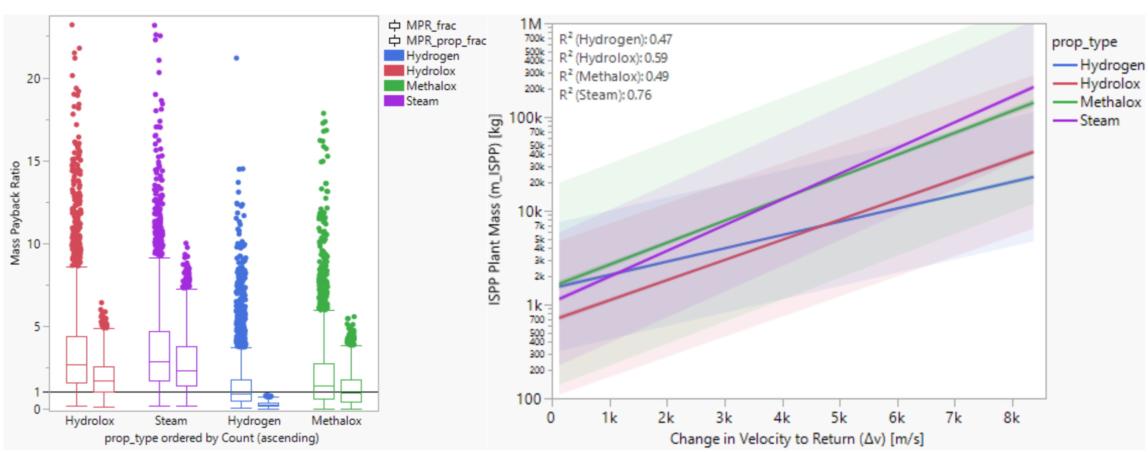


Figure 6-10: Mass payback ratios (with sample, propellant only) vs. propellant type, and plant mass fits vs. change in velocity by propellant type for experiment 2

Methalox fared better on average in experiment 2 as compared to experiment 1. The median of both MPRs used was higher (Figure 6-10 vs. Figure 6-3), and the plant mass regression upon change in velocity appeared to shift up less than the other propellant types (Figure 6-10 vs. Figure 6-5). Though hydrogen also got a boost to MPR, all of its cases still had $MPR_{PROP} < 1$. The slope of the hydrogen plant mass fit appears to have decreased though.

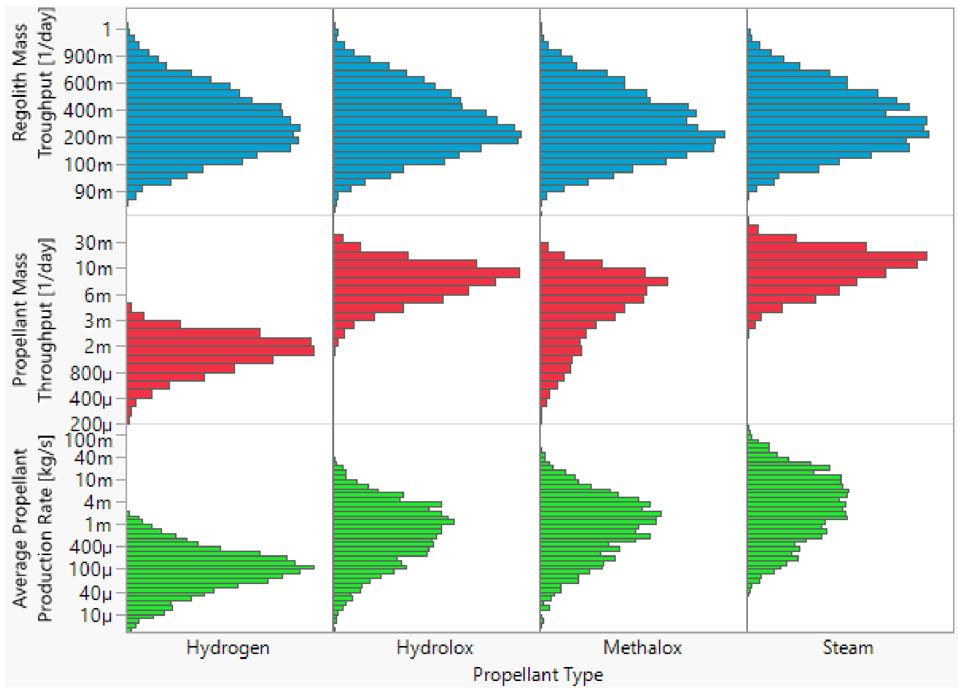


Figure 6-11: Regolith (f_{REG}) [1/day] and propellant (f) [1/day] mass throughput, and average propellant production rate ($\dot{m}_{PROP}$) [kg/s] distibutions in experiment 2

Another interesting lens to view the performance of sized concepts is overall mass flows. Figure 6-11 shows two forms of mass throughput describing matter handled per equipment mass per Earth day, along with the average propellant production rate. The average propellant production rate appears to increase as specific impulse decreases (values in Table 5-3). The regolith mass throughput distribution appears relatively invariant across propellant types, with each sized concept processing a quarter of its equipment mass in bulk NEO regolith on average each Earth day. Propellant mass throughput is several orders or magnitude less than that of regolith, with hydrolox and steam tending to have more mass efficient processing equipment. Hydrogen ISPP has lesser propellant demands, but also appears to be less mass efficient at producing that propellant. Steam ISPP has the greatest propellant production rates, though appears to use more mass efficient equipment.

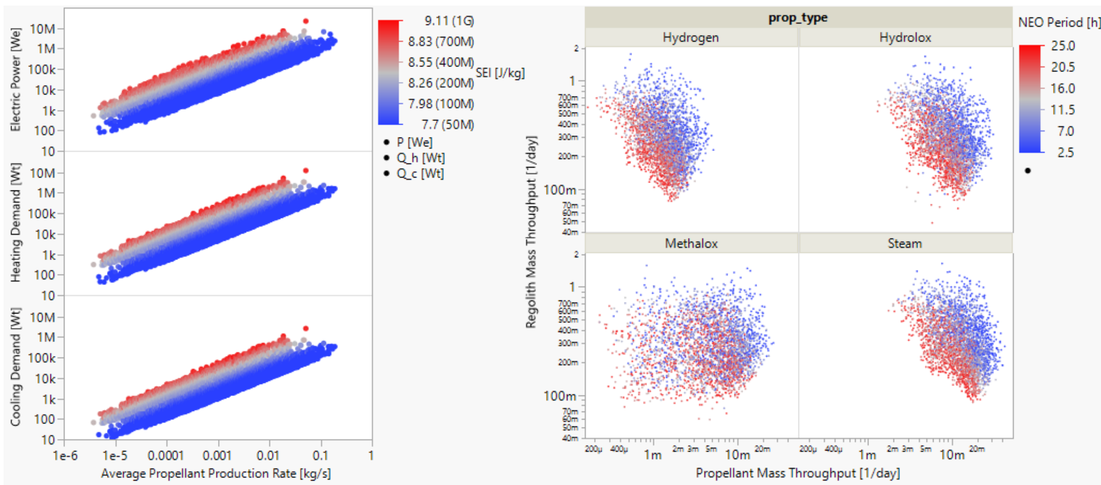


Figure 6-12: Energy useage rates (P, Q_C, Q_H) vs. average propellant production rate ($\dot{m}_{PROP}$) shaded by specific energy intensity (*SEI*) on left. On right is regolith mass throughput (f_{REG}), versus propellant mass throughput (f), by propellant type and shaded by NEO rotation period (t_{PERIOD}). Both are for experiment 2.

Both mass throughput metrics appear to be related to the period of NEO rotation for hydrogen, hydrolox, and steam as shown in Figure 6-12 on the right. Methalox shows greater variability, possibly due to a dependence on carbon as well as hydrogen availability. An increase in hydrogen concentration appears to correspond to an increase in the propellant mass throughput. The regolith mass throughput appears to increase with the overburden proportion. Of the three mass flow metrics, energy usage appears to be best explained by the average propellant production rate, as shown in Figure 6-12 on the left. Spread is well explained using Specific Energy Intensity (SEI) [J/kg], or the aggregate amount of energy (electric, heating, and cooling) used per mass of propellant produced. SEI is an insightful metric to explore, showing up in several important relationships.

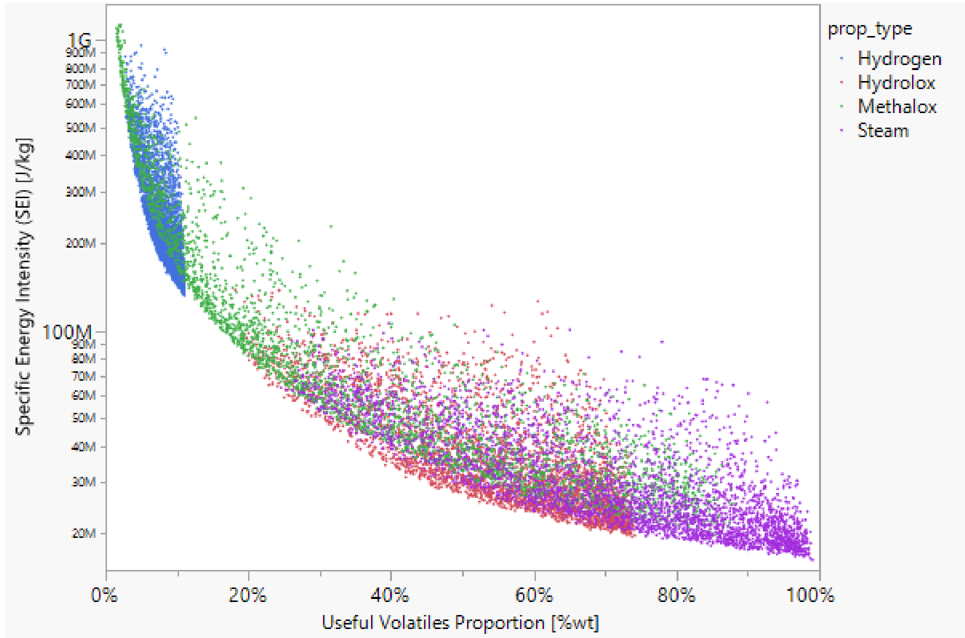


Figure 6-13: Specific energy intensity versus useful volatile proportion

For one, the minimum achievable SEI appears to be limited by the useful volatiles proportion as shown in Figure 6-13. This relationship holds across the four propellant types considered. There appears to be a set of pareto frontiers following an inverse curves, with slightly different dominated values achievable for each propellant type. It should be noted that the global optimum is in the bottom right, since lower energy expenditure and a greater use of evolved materials are both indicative of a more efficient design. Inefficiencies in volatile use can be attributed to non-stochiometric combustion leaving excess oxidizer, as well as unused byproducts like sulfur dioxide. However, utilizing additional feedstocks has situationally dependent utility, as evidenced by the large variation in useful volatile proportion of 1%wt – 87%wt for methalox resulting in a similarly large variation in SEI.

Another interesting relationship exists between SEI and the propellant mass payback ratio (MPR_{PROP}), as shown in Figure 6-14. SEI and the time on station together explain most of the variation present in MPR_{PROP} from Figure 6-10, across propellant types.

Another set of pareto frontiers appears to be present in Figure 6-14, with the dominated values constrained by the time on station allotted. The optimum value is in the upper left corner, with lower energy use and increased return on mass invested desirable.

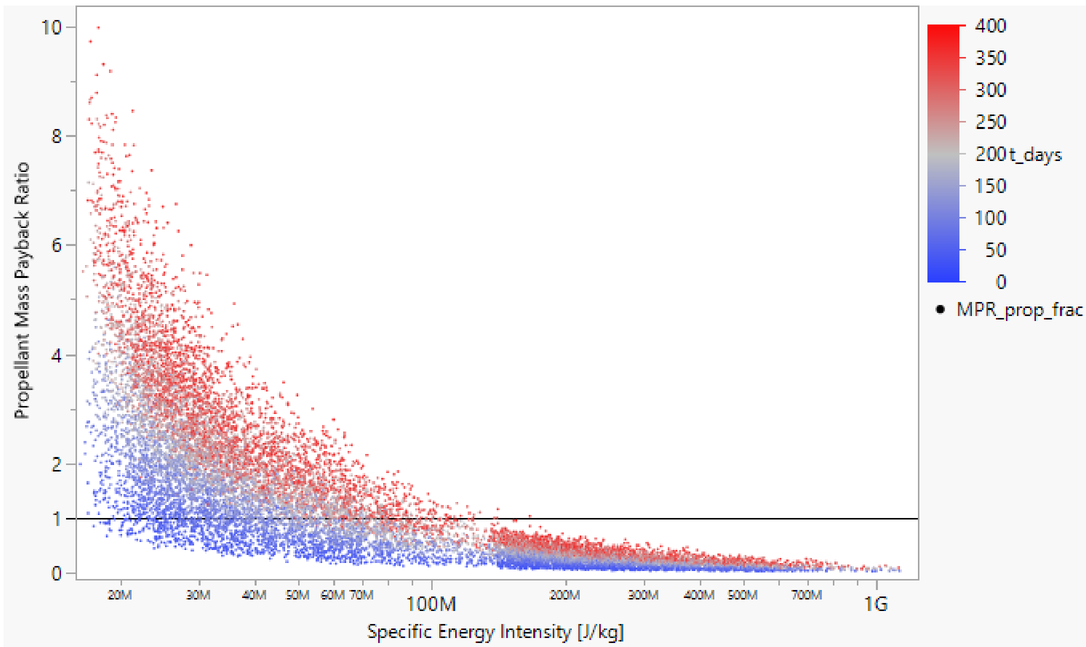


Figure 6-14: Propellant mass payback ratio vs. specific energy intensity by time on station. $MPR_{PROP} < 1$ means sample mission mass is not reduced by ISPP.

From looking at the large number of cases simulated in E2 a pattern emerges. Figure 6-9 shows that the concentration of elemental hydrogen heavily influences the useful volatile proportion. Figure 6-13 links a greater useful volatile proportion to decreased specific energy intensity. Figure 6-14 shows that lower specific energy intensity and longer time on station lead to an increased propellant mass payback ratio. The thermal and power systems providing energy services tended to account for at least two thirds of the sized plant mass as per Figure 6-7, with at least three quarters of demanded energy tending to come from extraction and thermal systems as per Figure 6-8. It is important to note that the energy use fraction distributions for the extraction and thermal systems closely mirror each other (Figure C-7 vs. Figure C-12). This is likely due to infrared lamps for to provide primary heating for extraction are currently sized in the thermal system, with their electrical and cooling demands mirroring heating from extraction. Thus, it can be said that the extraction module is driving the lion's share of energy use and therefore indirectly attributable for at least half the total sized plant mass in the majority of sized concepts examined in this work.

Conjecture 5 (C5)

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.

In addition, it would appear that methalox is more restricted in use than originally anticipated. In Figure 6-9, it is observed that roughly five times as much weight percent of carbon atoms is needed versus hydrogen atoms to achieve a higher useful volatiles fraction than hydrolox or steam. In concert with Figure 6-13 and Figure 6-14, this implies that far more energy is required to create enough methalox propellant in contrast to hydrolox for most cases considered. This effect is likely due to the need to process additional regolith to obtain more carbon. Thus a major hole in hypothesis 5 is found, on account of methalox propellant being too carbon limited in most cases to perform well.

CHAPTER 7. CONCLUSIONS

To conclude this work, the research questions that guided investigation are reviewed. The main takeaways are discussed, followed by recommendations for future work.

7.1 Resolution of Research Questions

Though the five research questions and their accompanying resolutions are distributed throughout the thesis, it is worth reviewing them one by one to recap the work. The research goals describe the primary thrusts of this work in non-technical (Focus of Research) and industry appropriate terminology (Research Objective and Selected Mission). In this way, this thesis aims to advance current knowledge in the field, and make the existing knowledge more accessible to a wider audience.

Research questions (Q#) are structured by the methodology to answer the research objective, and divided into two types. Literature based research questions (Q1, Q3, and Q4) are answered with a conjecture (C#) using deductive logic by building upon existing sources. Experiment based research questions (Q2 and Q5) have an associated hypotheses (H#) and research plan (P#) created in response to answer them. An experiment (E#) is formulated to test each hypothesis, with a result (R#) summarizing conclusions.

7.1.1 Research Goals

It is reasonable to ask if the overarching goals for this work were met. These research goals define the scope of this work, and guide its main thrusts. This thesis aims to show that Near Earth Object (NEO) In-Situ Resource Utilization (ISRU) is more feasible than previously believed, by providing a more comprehensive treatment of the required functionality and the means to deliver it.

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

The research objective is a more specific form of the focus of research.

> **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).

These are complemented by the selected mission, selected following C4.

> **Selected Mission**
>
> 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).

These statements helped structure this work, and can reasonably be said to have been achieved if the following five research questions are resolved. These research questions form the methodology created for conceptual comparisons depicted in Figure 3-3.

7.1.2 Research Question 1: Conceptual Comparisons

> **Research Question 1 (Q1)**
>
> How can comparisons between In-Situ Resource Utilization (ISRU) System of Systems (SoS) be done systematically at the conceptual level?

Since 1C answers 1Q satisfactorily, the first research question is considered resolved.

Conjecture 1 (C1)

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.

7.1.3 Research Question 2: Morphological Options

Research Question 2 (Q2)

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?

Q2 aims to establish a baseline design concept, with the research plan to do so below. Note that the most feasible alternative is interpreted to have the fewest identified obstacles

Research Plan 2 (P2)

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 a baseline.

A hypothesis was formed based upon commonalities observed in existing concepts.

Hypothesis 2 (H2)

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.

After the heavy lifting of creating the morphological matrix and determining a sizeable number of TRLs to use for comparison, selections can be made. Note that the concept containing the fewest number of low TRL options is assumed to have the fewest obstacles remaining in development, and can thereby be interpreted as the most feasible concept considered. With the resulting selected concepts, comparisons can be made qualitatively by noting the number of TRLs below a given threshold as a proxy for the degree of development risk. Table 4-7 shows that the hydrolox concept contains the fewest low-TRL options of the concepts considered, and is therefore designated the baseline for comparison in R2, which satisfactorily answers Q2.

Result 2 (R2)
The hydrogen-oxygen (hydrolox) propellant design selected through narrowing down options using Technology Readiness Levels (TRLs) should be a better baseline for comparison than the Honey Bee concept.

7.1.4 Research Question 3: Key Parameters of Interest

Research Question 3 (Q3)
What parameters are needed to adequately describe a Near Earth Object (NEO) sample return mission with In-Situ Propellant Production (ISPP)?

Q3 aims to constructively address the need to manage a large number of parameters for the sizing code by providing guidance on which parameters require additional attention to be paid. The focus here is on determining what changes between NEO destinations and providing a range of reasonable values and a nominal value to use. The alternative is to provide a reasonable default value, or construct multiple Design of Experiments to explore additional properties. By reducing the number of variables considered in an intelligent fashion, it is easier to glean trends in the results. As a result of looking at NEO destinations three categories of parameters are considered and result in nine inputs of principal interest. Since these parameters are able to be used successfully to conduct the propellant trade study for Q5, it is felt that C3 satisfactorily answers Q3.

> **Conjecture 3 (C3)**
>
> The ten parameters selected adequately capture the mission characteristics, solar radiation effects, and NEO composition: $PROP\_TYPE$ [String], Δv_{RT}[km/s], m_{SAMP}[kg], $d_{SUN,min}$[AU], $d_{SUN,max}$[AU], C_C[%wt], C_H[%wt], C_S[%wt], t_{STAY}[days (Earth)], t_{PERIOD}[hours (Earth)]

7.1.5 Research Question 4: Selecting an Application for ISRU

> **Research Question 4 (Q4)**
>
> What is the most feasible application for NEO ISRU presently?

Significant discussion was invoked in § 3.5 on mission selection to address 2Q. Note that feasible is interpreted to mean having the fewest identified obstacles to success. It was discussed which space resources are available on NEO, as well as the impact of policy considerations and crew being present. Through use of deductive logic, 2C was arrived at and a mission selected. "Sample return from Near earth object with In-situ Propellant production Technology demonstrator" (SNIPT) is the proposed program name to develop such a design. Since the stated goals were achieved, success was achieved.

> **Conjecture 4 (C4)**
>
> In-Situ Propellant Production (ISPP) using NEO resources for a sample return mission is the most feasible ISRU SoS application presently.

7.1.6 Research Question 5: Propellant Trade Study

Research Question 5 (Q5)

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

An overarching trade study on propellant selection to guide this work was initiated as part on Q5, executing the developed methodology according to the corresponding P5.

Research Plan 5 (P5)

Construct morphological matrix, using functional decomposition. Down-select concepts qualitatively for each propellant considered using TRLs in line with Q4. Determine input parameters in line with Q5, then create modules in sizing code to correspond with selected concepts. Verify and validate as appropriate, then screen values using quantitative methods.

Three hypotheses were made, with H5 being decomposed into H5.1 and H5.2.

Hypothesis 5 (H5)

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.

What makes a 'demanding target' is analyzed by orbital characteristics and composition.

Hypothesis 5.1 (H5.1)

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

H5.1 proven true by virtue of being the most significant effect noted in Figure 6-6 using a false discovery rate P-test. Thus, Δv does have the largest effect on the sized plant mass.

Result 5.1 (R5.1)

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

However, H5.1 has also been proven partially incorrect due to the worse performance of methalox in E1, though revealed to be better in a specific high carbon niche during E2.

Hypothesis 5.2 (H5.2)

If sized ISPP plant mass sensitivity to NEO composition is analyzed, then the availability of water will have the greatest contribution to variability.

The useful proportion of volatiles (*UseVols*) appears to have clearer impacts on plant sizing that the useful regolith proportion (*UseReg*). H5.2 has been proven true by Figure 6-9, with elemental hydrogen (C_H) [%wt] representing water in present in the NEO.

Result 5.2 (R5.2)

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.

Though the supplementary hypothesis on methalox performance has a grain of truth, since methalox has a higher useful volatiles proportion if a 5:1 or greater mass ratio of carbon to hydrogen is present. Still, this additional dependency made methalox less robust.

Conjecture 5 (C5)

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.

As a result of the sizing of a significant number of varied cases for experiment 2, a set of possible causal relationships was found by linking Figure 6-9, Figure 6-13, and Figure 6-14 together to form C5. Extraction tends to indirectly account for at least half of the sized plant mass on average, when accounting for its outsize energy demand.

With the final research question marked as satisfactorily resolved, this review of research questions is concluded. Since the methodology in Figure 3-3 was followed to make meaningful comparisons, the research objective is judged to have been achieved.

7.2 Main Takeaways

In line with the resolved research questions, the first takeaway from this work is that morphological matrices focused on discerning between technological solutions are a useful tool to enable systematic meaningful comparisons in the pre-conceptual design phase. Of course, that is not all this thesis has done. A number of novel contributions of note have been made to the field of ISRU, along with many, many more trade studies enabled.

7.2.1 Novel Contributions

Throughout the course of this work, several interesting developments arose that are believed to have advanced research in the field. Many arise from applying techniques from other related fields to ISRU, while others are distinct in their own right.

- ISRU as space infrastructure
- Review of proposed NEO ISRU SoS concepts
- Idea for SNIPT mission proposal
- Morphological matrix of alternatives for NEO ISPP SoS
- 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, with corresponding ranges of values provided.
- Identification of possible relationships between select NEO ISPP SoS metrics
- Propellant trade study from ISRU perspective

7.2.2 Enabled Trade Studies

In addition, a number of trade studies are now possible to conduct using the morphological matrix and the sizing code in their current state. Examples of such include:

- Comparing alternate NEO destinations (esp. Δv, aphelion, perihelion, composition)
- 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)
- 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
- 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)

7.2.3 Design Recommendations for NEO ISRU Concepts

Throughout the development process for the sizing code and morphological matrix, a number of informal trade studies and were conducted. A few pertinent observations are stated here for reference. First and foremost, no existing NEO ISRU concept was functionally complete (Table 4-4), and the average concept was not getting meaningfully better over time (Figure 4-6). Table 7-1 shows the 23 categories where at least 1/3 of existing NEO ISRU concepts did not appear to document a selection. Use of the morphological matrix developed herein (Table 4-5) should help prevent future omissions. Thermal management has been historically neglected in ISRU concepts. Three of the five thermal system functions identified are in the top five most commonly overlooked functions in existing NEO ISRU concepts, with the fourth and fifth also in Table 7-1.

Table 7-1: Most commonly overlooked functionality within existing concepts

Group (System)	*Category (Subsystem)*	*Concepts Without [#]*	*Proportion Missing [%]*
Power	Energy Storage	16	80%
Refining	Quality Control	15	75%
Thermal	Distribution	15	75%
Thermal	Heating [Secondary]	14	70%
Thermal	Heat Exchangers	14	70%
Wastes	Byproducts & Excess	14	70%
Structures	Support Structure	14	70%
Storage	Insulation	13	65%
Avionics	Computation	13	65%
Avionics	Deep Space Comms	13	65%
Thermal	Cooling	12	60%
Structures	Rotation Control	11	55%
Structures	Relative Motion	9	45%
Return Vehicle	Return Type	8	40%
Prospecting	Wave Type	8	40%
Prospecting	Sampling	8	40%
Material Handling	Fluids (Liquid & Gas)	8	40%
Material Handling	Work Input	8	40%
Avionics	Local Comms	8	40%
Thermal	Beam Transmission	8	40%
Avionics	Autonomy	7	35%
Power	Electrical Generation	7	35%
Wastes	Tailings & Overburden	7	35%

The performance of the sized SoS and systems observed were also far lower than guesstimated by previous sources such as Sonter (1997) and Hein (2019) [62], [99]. A reasonable goal for mass payback ratio appears to be $MPR \approx 5$, not 100, for a single mission based upon Figure 6-3 and Figure 6-10 [99]. The regolith mass throughput was found to be on the order of tens of grams regolith per kilogram equipment per day $f_{REG} \approx 0.3\ \mathrm{kg/(kg * d)}$ in Figure 6-11, not tens of kilograms regolith per kilogram equipment per day [62]. When applied to systems, the mass throughputs were found to be on the order of one kilogram processed per kilogram equipment per day (Figure C-7, Figure C-8, & Figure C-10), not hundreds, with the exception of the refining module (Figure C-5) which saw greater variability [99], [159]. It is recommended for the ISRU community to design and model equipment around more achievable values for these metrics and include the effects of supporting hardware to avoid overselling near-term capabilities.

To increase the propellant mass payback ratio (MPR_{PROP}) $[\mathrm{n.d.}]$ for ISPP, two main approaches have been identified. Following from Figure 6-14, these are reducing the Specific Energy Intensity (SEI) [J/kg] or lengthening the useful time for propellant production. The simplest solution is to extend the time on station in the mission design, allowing for smaller sized components. Note that maintenance and reliability considerations are not factored in, so the disbenefits of extended operation are unknown. It is also possible to operate in the dark as well as light phases of the NEO diurnal cycle would increase the useful time for propellant production, though this would be an issue for solar thermal concentrators and related technologies. Another solution identified by existing concepts is to picking a sufficiently small diameter NEO target and arresting its rotation to permit the use of continuous near-uninterrupted sunlight [89]. Though experiments 1 and 2 assume round the clock operation (100% uptime in light and darkness) with infrared lamps and batteries after discounting 25% of the time on station for startup and shutdown procedures, these parameters can be varied in the sizing code developed.

To decrease SEI, energy use for the extraction of volatiles should be reduced. Power and thermal management support systems appear to play an outsize role in mass sizing (Figure 6-8), so reducing power or heat demand can significantly lower the mass of a system. The extraction system was found to indirectly account for around half of the sized plant mass on average from its outsize energy demands to heat NEO regolith ~700 K to extract small quantities of volatiles (§ 6.2.3). One solution to reduce extraction energy usage is to develop better extraction technologies to increase the extraction efficiency and recover more desired volatiles from the same amount of ore. Another is to focus on prospecting for then excavating higher grade ores with more specifically desired space resources like water ice present in them (Figure 6-13). Seeking NEO destinations like comets with increased elemental hydrogen and equivalent concentrations could also be a possibility, though this must be weighed against increased Δv requirements, a shorter time on station, and interference from off-gassing (e.g. comet tail occluding radiators).

Though steam was the most common propellant proposed among existing concepts (35% steam, 20% hydrolox, 10% methalox), it may not be the best choice. Steam tended to have a higher MPR (Figure 6-3) but also relatively higher plant mass (Figure 6-10) and average propellant production rates (Figure 6-11). This is the result of a low specific impulse (Table 5-3) necessitating a greater propellant mass. The increased refining mass (Figure 6-7) and energy use (Figure 6-8) penalties from producing more chemically complex propellants were observed to be surprisingly small. Hydrolox fares best in this regard, with the increased specific impulse permitting the lightest plant mass on average, especially at lower Δv (Figure 6-5). It is worth looking into stochiometric combustion for liquid rocket engines to further decrease ISPP plant mass, with the increase in the useful volatiles proportion hypothesized to more than offset the reduction in specific impulse. Methalox is only recommended when composition of greater than 5:1 elemental carbon to hydrogen on a mass basis is present, as its useful volatile proportion is only higher than the other propellants considered in this region (Figure 6-9).

Hydrogen is an interesting case, tending to have the lowest plant mass at higher return Δv (Figure 6-10), yet consistently having $MPR_{PROP} < 1$ (Figure 6-3). The former is thought to stem from the much higher specific impulse (Table 5-3) characteristic of electric propulsion, while the latter from useful volatile proportions an order of magnitude below the other propellant types (Figure 6-9). It has been noted that some high power electric propulsion systems can utilize 'alternate propellants' (H_2, O_2, H_2O, CO_2, CH_4) to noble gasses, though only hydrogen was found to have a specific impulse value quoted in the literature [179], [194]. By changing the propellant type to a chemcial species produced in higher quntities by the ISPP SoS (e.g. oxygen), the useful volatile fraction would be substantially increased. The use of additional thrusters with different propellant types (e.g. one hydrogen and others oxygen) or mixed gas streams could further increase the useful volatile fraction. This is desireable, since a higher useful volatile fraction is linked to lower SEI which is linked to increased MPRs. It is hypothesized the use of multiple 'alternative propellants' in an electric propulsion system on the return vehilce would permit ISPP plants with lower overall mass and higher MPRs than most sized concepts in this work.

7.3 Recommended Future Work

There are also additional modeling aspects that could be interesting to study, but were omitted to limit the scope. Each of these aspects could become potential thesis topics in their own right, and are thus considered recommended future work.

First and foremost, the sizing code should be extended to size all selected options in the baseline concept. Direct ISRU systems were prioritized for development, so it is primarily indirect ISRU systems that are missing sizing code corresponding to identified functions. Avionics and prospecting are not included in the sizing code at present, with limited inclusion of material handling and structure mechanisms. Heat exchangers, coolant loops, and separation equipment are not sized presently either, though station temperatures and heat loads are computed. Additional verification efforts are also worthwhile. Recognizing the absent subsystem masses as well as the novelty of the designs, fairly high values for system mass contingencies (30%) and overall SoS mass margin (30%) were used by default to compensate. This has the effect of nearly doubling the overall ISPP plant mass, given the mass contingency is also applied to the return vehicle bare dry mass.

Secondly, additional functions could be added to the sizing code to enable evaluation of additional morphological options. A library of functions for each option in the morphological matrix is envisioned, possibly associated with an interactive reconfigurable matrix of alternatives containing a compatibility matrix. Example trade studies that could potentially be conducted with relatively minimal modifications to the sizing code include:

- Fission power versus photovoltaics with batteries, especially when varying uptime during the dark portion of the diurnal cycle on NEO.
- Novel electric propulsion concepts, esp. with non-standard propellants (e.g. oxygen [194]) or mixed gas streams to improve the useful volatile fraction
- Adding a second propellant to the return vehicle or permitting a mixed gas stream, seeking how the additional propellant mass but lower average specific impulse effects the sizing of both the ISPP plant and the return vehicle.
- Sublimation volatile yield versus maximum temperature used and composition; Note that a mapping function would be needed to relate max. and min. temperatures during extraction to the cumulative evolved species of each gas to intelligently vary the extraction efficiency parameters already included in the model. Multiple simulant gas evolution profiles could be used to account for compositional changes.
- Earth aerocapture, lunar gravity assist, and/or propulsive capture [104]. Note that ozone depletion may be a concern for frequent aerocapture [160].

Third, the impact of novel technologies or concepts could be evaluated by swapping out one or several sizing functions from the baseline design concept. In addition categories in the morphological matrix that lack high TRL options could be identified. Together, this could form a basis for Technology Identification Evaluation and Selection (TIES) studies. Results could be used to aid decision making on funding for future technology maturation and development efforts, or provide guidance on capabilities worth pursuing.

Fourth, the streamlined Technology Readiness Assessment (TRA) could be enhanced to consider other factors like compatibilities between technologies. The TRA conducted for this thesis was fairly simplistic, and could certainly be improved. The process conducted by Bazzocchi in his thesis is particularly noteworthy, for also assessing technologies for research and development degree of difficulty and technology need value [105]. These three metrics were then combined as indicators on a to compute proxies for likelihood and consequence for placement onto a risk matrix to assess concepts. A similar method could be used to better screen technologies for consideration in each category of morphological options discussed in this thesis.

Fifth, the sizing code could be integrated into a space logistics framework to provide more realistic ISPP plant masses or capture externalities from extended plant operation. A major benefit to doing so would be to permit the ISPP plant to be set up once then utilized in multiple missions throughout a campaign. This would likely substantially increase the mass payback ratio of the ISPP SoS, though gains should be discounted through capacity reduction from anticipated failures or the delivery of spare parts. A wrapper could be constructed to call the sizing code itself, or surrogate models could be formulated to relay trends in the sizing results for easier compilation or reduced runtime. For a good treatment of predicting spare part masses through reliability analysis in ISRU applications, the reader is referred to the dissertation by Do on MIT's HabNet [93]. The effects of changing the destination for the produced propellant or staging supplies away from where they are produced could also be examined within a space logistics framework.

Sixth, cost modeling of the proposed SoS or its constituent systems could be introduced. Note that this cost modeling is envisioned as more of a means of project lifecycle cost rather than the commercial viability of concepts. Possible metrics that could be used to help determine cost include: TRLs, sized mass per unit, and quantity used versus manufacturing learning curves. A net present value calculation could also be included to discount the extra-long mission timescales in economic terms, especially for campaigns.

Seventh, Bayesian methods could be applied to capture input distributions as a probabilistic alternative to space filling Design of Experiments (DoE). This would permit better handling of uncertainties in inputs and expected values of outputs in an otherwise deterministic sizing code. Nonuniform probability density functions of NEO properties similar to those documented by Bazzocchi are recommended to be used, especially for NEO composition where there is less agreement in the field [105]. A surrogate model of sizing code could then be used as mapping function between random variables (of the inputs and outputs), as shown in Figure 7-1.

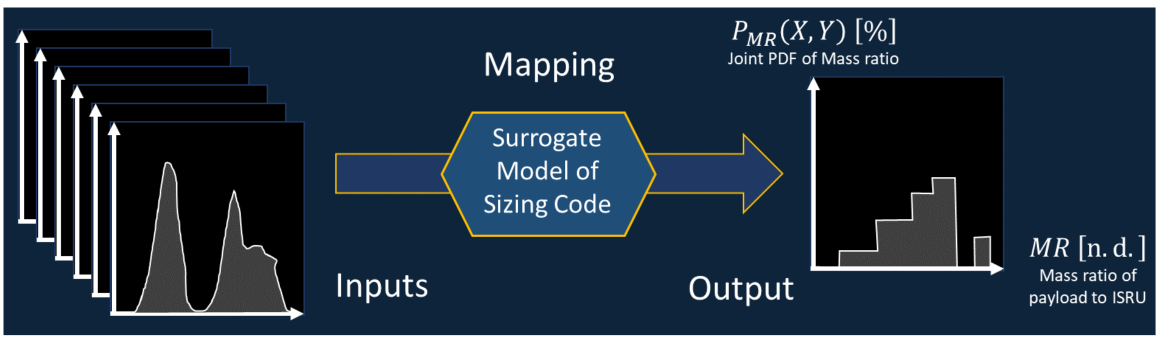


Figure 7-1: Using surrogate models as a mapping function

Finally, treatment of requirements through Model Based Systems Engineering (MBSE) techniques would be worthwhile to include. Constraints upon the available morphological options as well as permissible values for input parameters could be posed as requirements. These requirements could then have their impacts gauged as constraints upon the design space by assessing the performance of many design concepts. A fully interactive model could be created by translating the morphological matrix into a Systems Modeling Language (SysML) diagram and associating the sizing code elements through integration with ModelCenter. In this way, design concepts could be rapidly created and evaluated in an automated fashion, with links back to requirements of interest.

APPENDIX A. REVIEW OF EXISTING CONCEPTS

Upon a review of the literature, a significant yet manageable number of serious proposals for Near Earth Object (NEO) In-Situ Resource Utilization (ISRU) concepts were found. An individual look at each concept was deemed worthwhile, but of too much detail for inclusion in the main body of this work. A compromise was reached by creating Table 4-2 as a means of summarizing the design choices of the existing NEO ISRU concepts, while putting additional relevant information in this appendix. Visualizations are included to permit visual as well as textual comparisons between designs and resource flows.

While conduction this review, it was noted that variation of concepts within a research group tended to be much less than between groups. There appeared to be little cross-pollination occurring, though convergent evolution was observed. Thus, the decision was made to treat design concepts primarily by the groups working on them instead of the concepts directly. Presented concepts were observed to evolve over time as development progressed. In particular, small, medium, and large sized variations on similar concepts emerged from more thoughtful groups.

A.1 Honey Bee (TransAstra Corporation)

TransAstra Corporation has focused on developing extraction techniques, especially thermal spalling [11]. The Honey Bee concept in Figure A-1 is built around their ‘optical mining’ technique. A sperate idea for methalox refining system is in Figure A-2 [20].

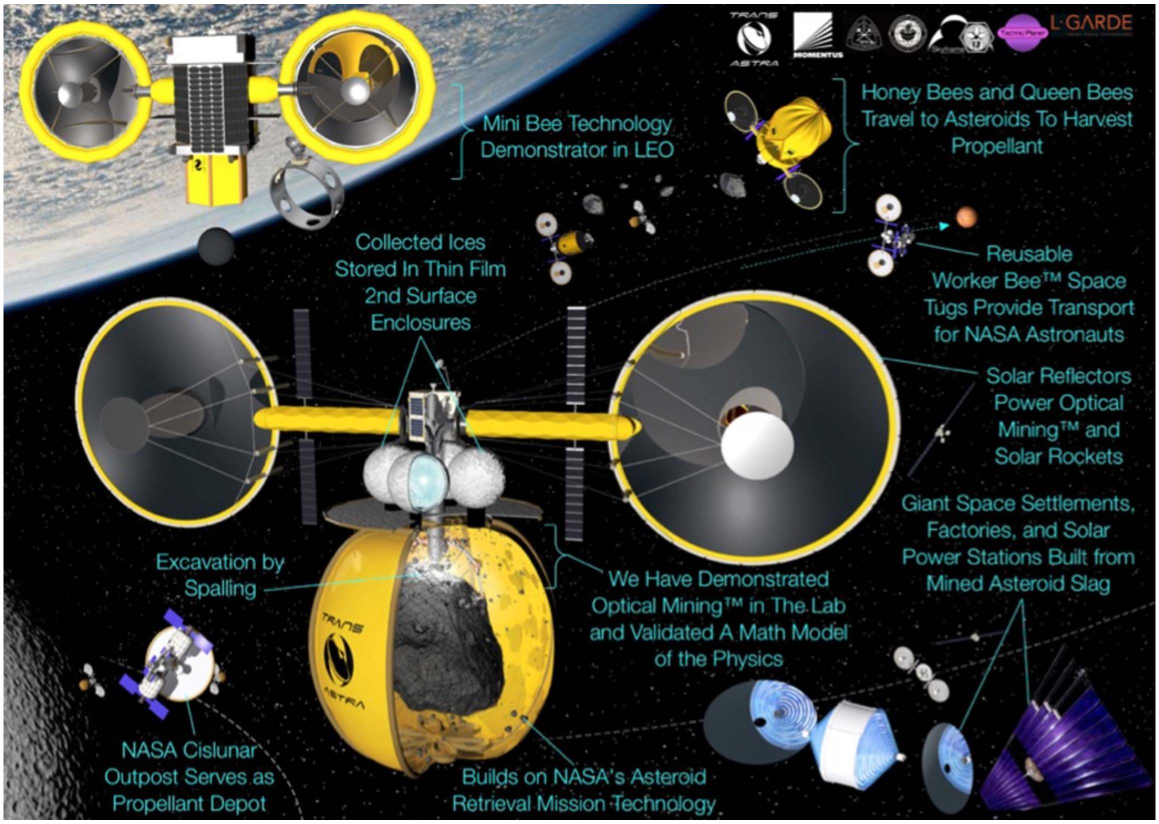


Figure A-1: Honey Bee spacecraft with Mini Bee technology demonstrator [96]

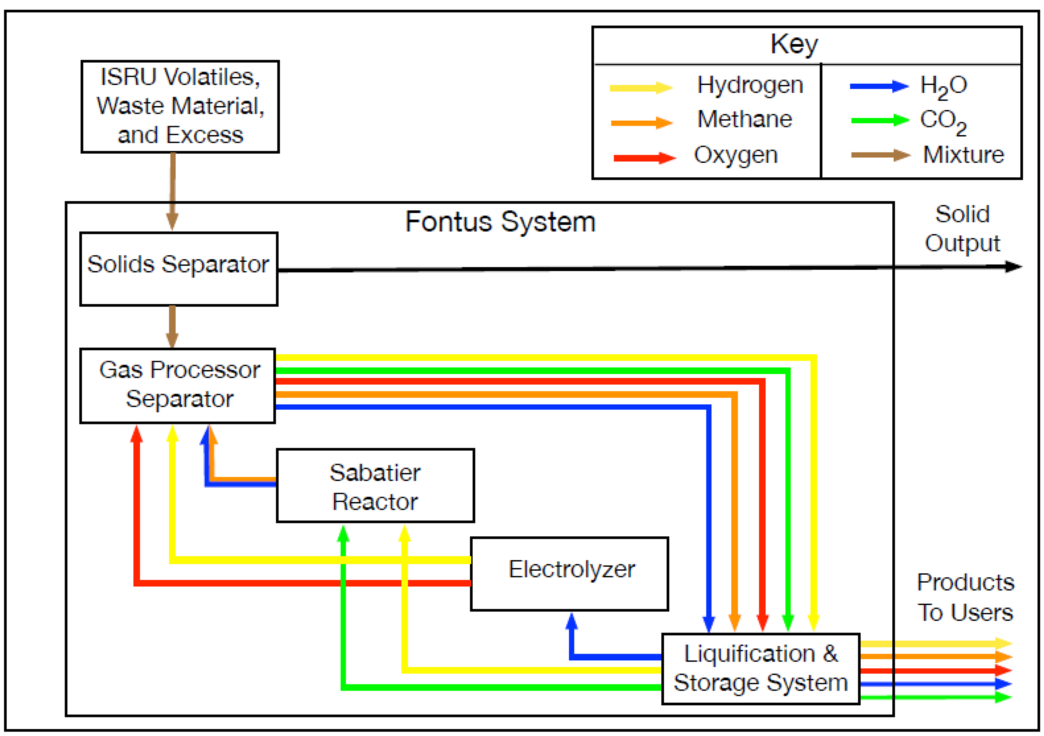


Figure A-2: Fontus refining system concept for methalox production [11]

TransAstra has recently verified the concept in experimental testing on asteroid simulants develop the technology up to TRL 3-4 [96]. Their work has been primarily funded through NASA NIAC and SBIR funding to date, with a NIAC Phase 3 award of $2M recently awarded to launch the ‘Mini Bee’ technology demonstraitor to orbit to test ‘optical mining’ on a co-hosted CI-simulant asteroid, as visualized in Figure A-1. This award is in conjunction with Momentus Space, L’Garde Inc., Techno Planet Inc., UCF CLASS, and the Colorado School of Mines.

A.2 Spider (HoneyBee Robotics)

HoneyBee Robotics is a recurring NASA contractor that has focused its IRSU efforts on developing volatile extraction mechanisms, such as pictured in Figure A-3 [9].

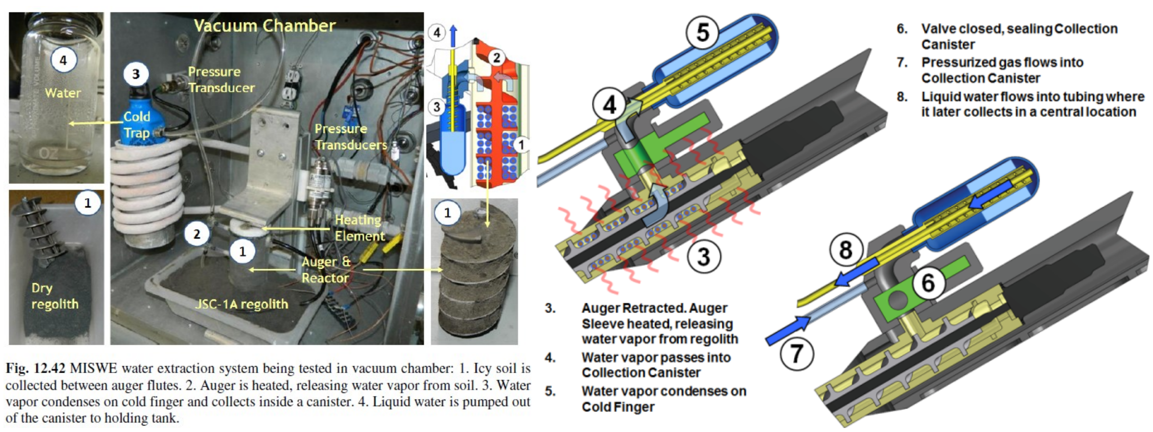


Figure A-3: HoneyBee Robotics extraction experiments and apparatus [101], [195]

Their notinal asteroid mining framework is in Figure A-4, with a concept they collaborated on for large NEO (Robotic Asteroid Prospector) shown on left and concept for small NEO developed in house (spider) on right. The World Is Not Enough was developed as a lab-scale prototype extraction and processing system, which was successfully tested upon an early C1-asteroid simulant [88]. Their mobile in-situ water extractor has been further developed into the spider water extraction system under SBIR funding with NASA KSC Swampworks and Embery-Riddle Aeronautical University, which is projected to achieve TRL 5 in late 2019 [196]. Note that HoneyBee Robotics collaborated with Astrotecture on the design for the Robotic Asteroid Prospector, though technologies for Spider appear to receive more development effort internally.

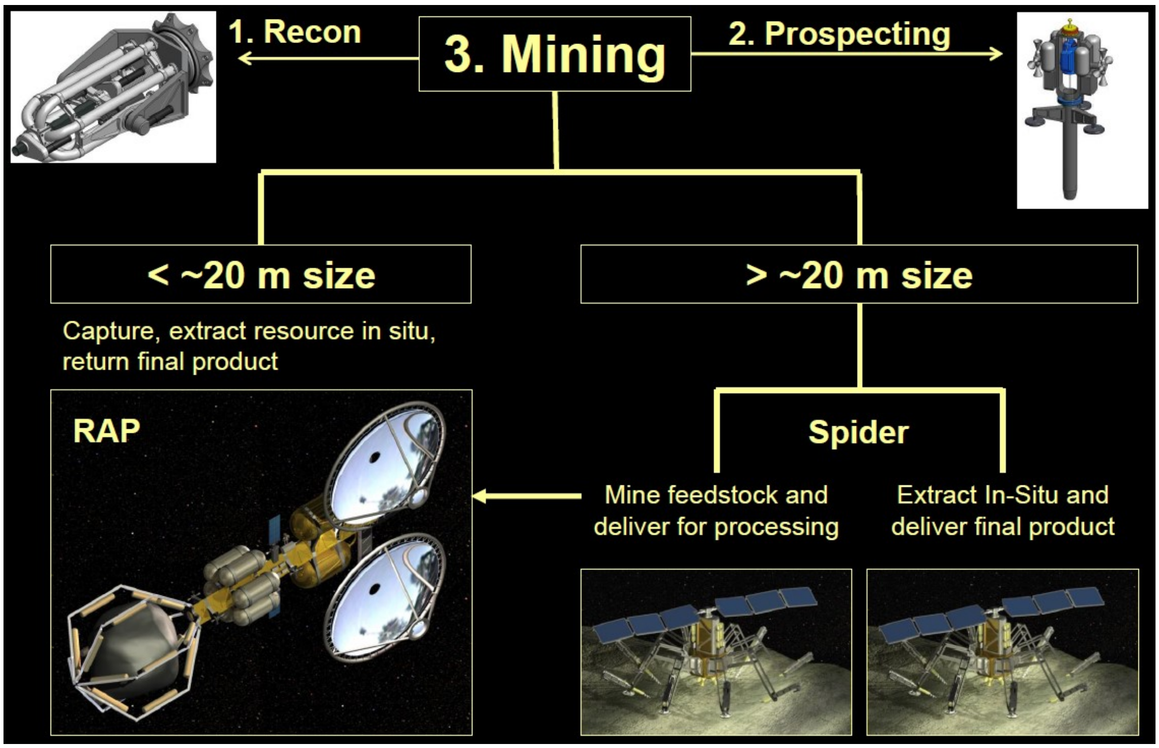


Figure A-4: HoneyBee Robotics exploration hierarchy. Note the Robotic Asteroid Prospector is proposed for smaller targets, and the Spider for larger ones [9]

A.3 Robotic Asteroid Prospector (Astrotecture et al.)

A consortium of partners led by Astrotecture developed the Robotic Asteroid Prospector concept shown in Figure A-5 [81]. This concept is noted for its proposed sampling and retrieval approach, as well as recasting the 'optical mining' approach developed by TransAstra in a new light. This was the third most fleshed out NEO ISRU concept found, and one of the few that borrowed ideas from other concepts.

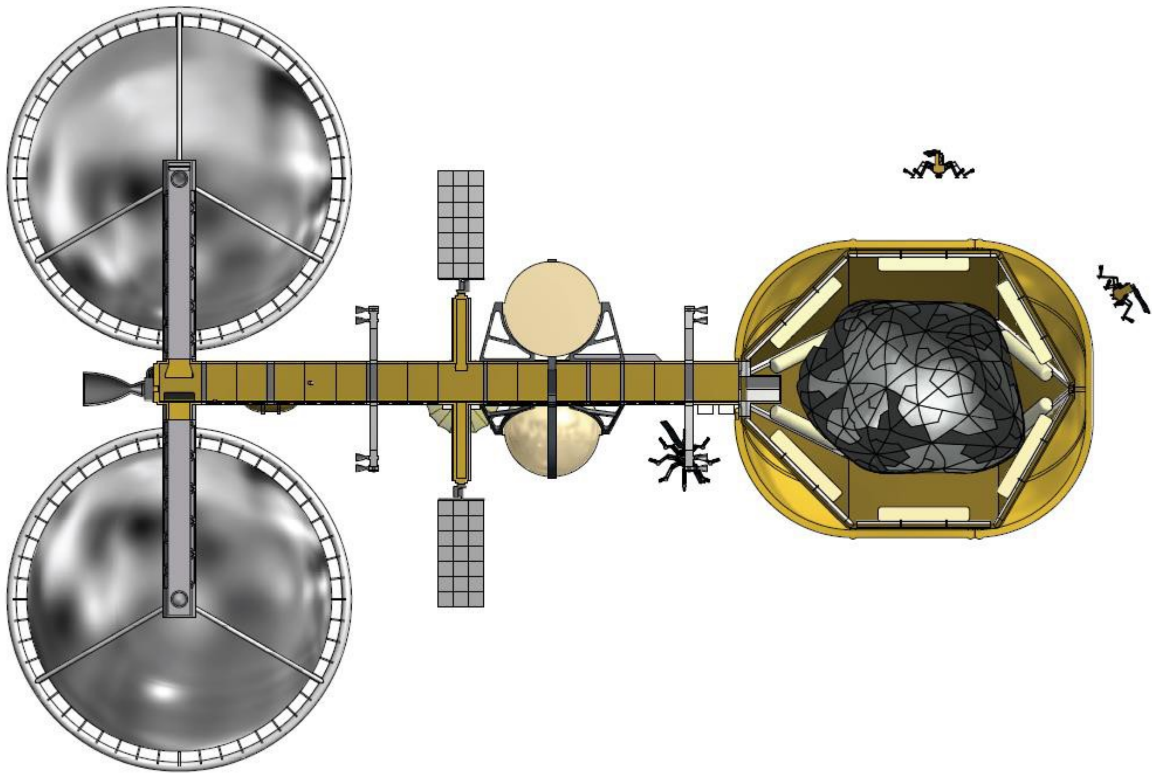


Figure A-5: Astrotecture et al. Robotic Asteroid Prospector concept [81]

A.4 Cornucopia (Star Technology & Research)

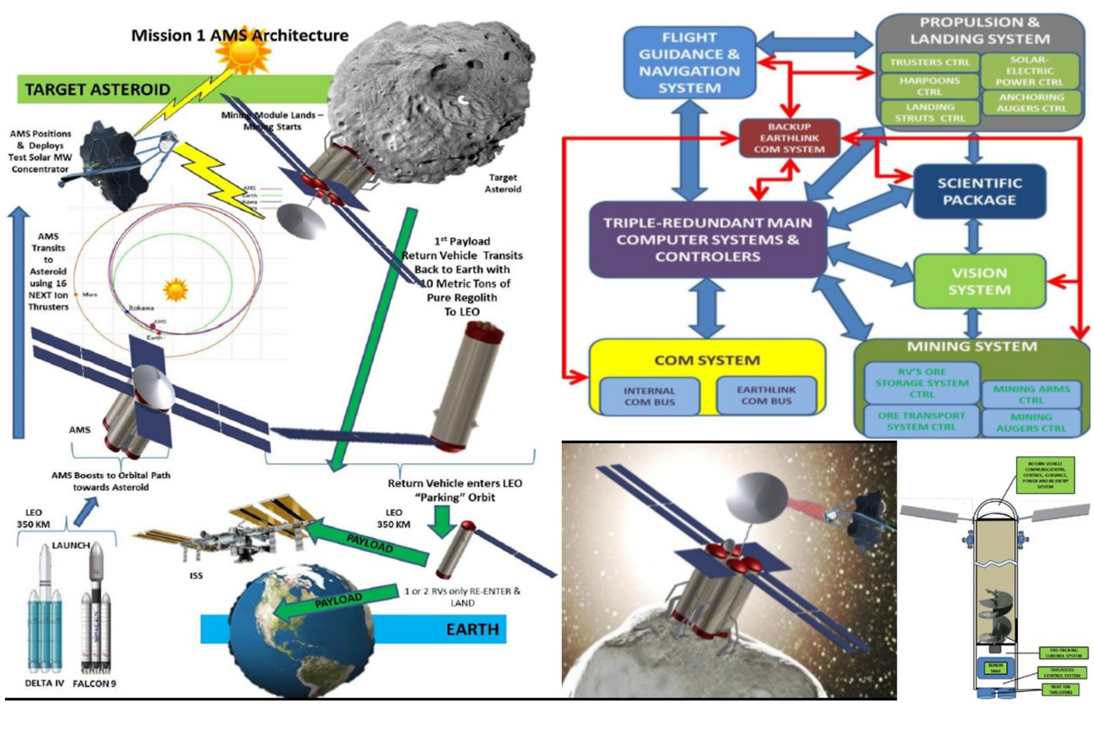


Figure A-6: Cornucopia mining system [153]

Star Technology & Research is a consulting firm that took a different track, conducting a paper study focused on material handling for a hypothetical asteroid mining system [153]. They entitled their SoS the ‘Cornucopia mining system’, as shown in Figure A-6. Their use of modular augers in tubes to move asteroid regolith and preform sample return missions is interesting along with the decomposition of required subsystems, though the rest of the design has not been developed sufficiently for meaningful comparison. This NEO ISRU concept appears to be a one-off offhand effort, with no follow-up from the research group observed.

A.5 Hein et al. (Initiative for Interstellar Studies)

The Initiative for Interstellar Studies focused on the economic viability of asteroid mining operations, and how the equipment could be miniaturized to arrive at a minimum viable product of sorts [62]. A visualization of the concept of operations is in Figure A-7.

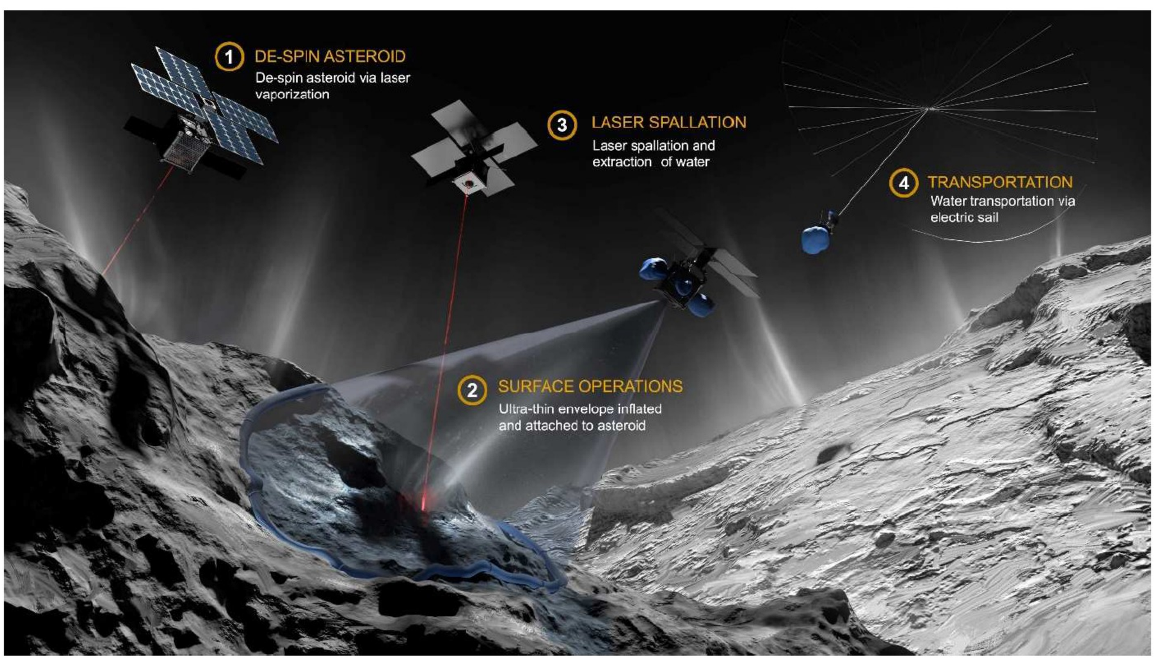


Figure A-7: Small spacecraft voltatile mining architecture [62]
Image: Efflam Mercier / Initiative for Interstellar Studies

Their concept has a number of interesting features, consisting of a swarm of 27 singe unit CubeSats. These satellites are to conduct a de-spin maneuver for the NEO, attach a translucent membrane to the NEO surface, fire an ablative laser to evaporate volatiles, condense the water ice, and return samples using a solar sail back to LEO. This NEO ISRU concept appears to be a one-off effort, with follow-up uncertain.

A.6 RockBreaker (Georgia Tech)

The 'Rock-Breaker' concept hails from the Aerospace Systems Design Laboratory at the Georgia Institute of Technology, and is notable for its unique excavation techniques proposed as shown in Figure A-8 [146], [197]. Though at least three papers were published on aspects of this NEO ISRU concept development appears to have stalled, with no recent publications on the concept.

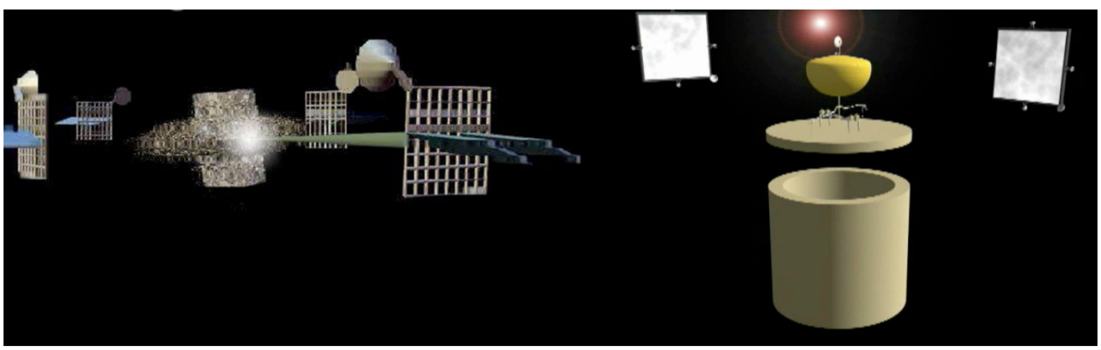


Figure A-8: Georgia Tech Rock-Breaker constructing a cylindrical habitat [146]

A.7 Konstantin (Catalyst Corporation)

Note that the Catalyst Corporation concept is a fictional entity taken from a recent hard science fiction novel [155]. However, the systems engineer who wrote the book put enough thought into fleshing out the concept to make it plausible that it is considered herein. This concept is particularly notable for being the only crewed operation considered, due to their presence being sufficiently justified through addressing maintenance reliability and operations concerns. Note that solving these concerns comprises a large chunk of the plot in the novel. Visualizations created by the author for various vehicles are featured in Figure A-9. Additional development work on this concept by the author is deemed unlikely, since the source is a stand-alone novel.

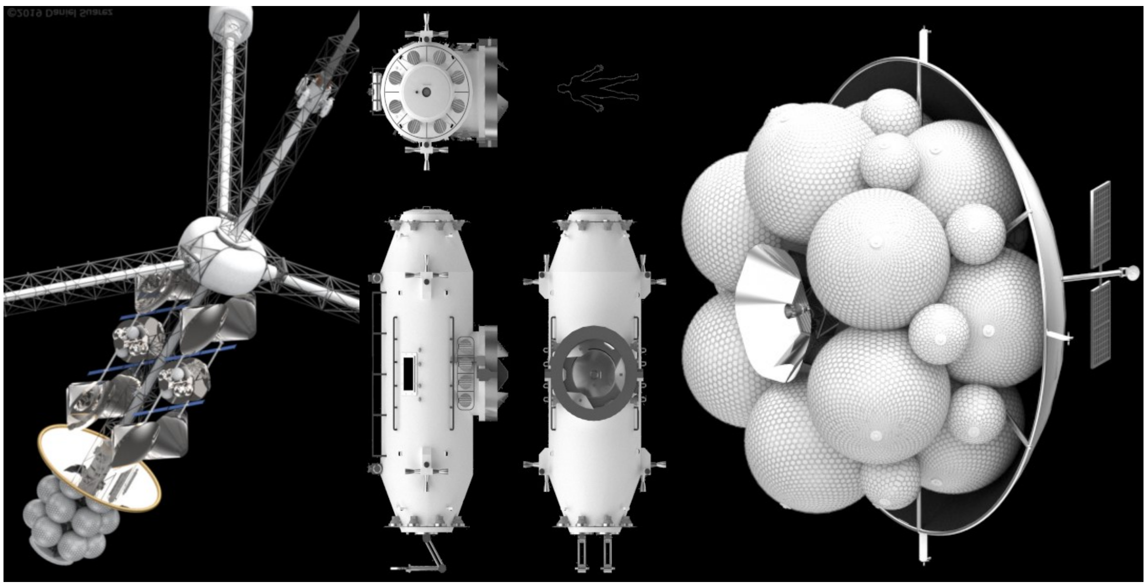


Figure A-9: Konstantin, Mule, and robotic tug vehicle concepts [155]

A.8 O'Leary et al. (NASA Ames)

O'Leary et al. proposed a NEO ISRU concept within the Space Resources and Space Resources compendium published by NASA Ames in 1979 [156]. A high-level schematic of the processing concept proposed is shown in Figure A-10. Note that crewed operation was assumed for maintenance purposes, with a mass driver envisioned for propulsion using tailings as propellant. This concept was updated slightly in the 1980's, though relevant publications were not retrievable by the author [198].

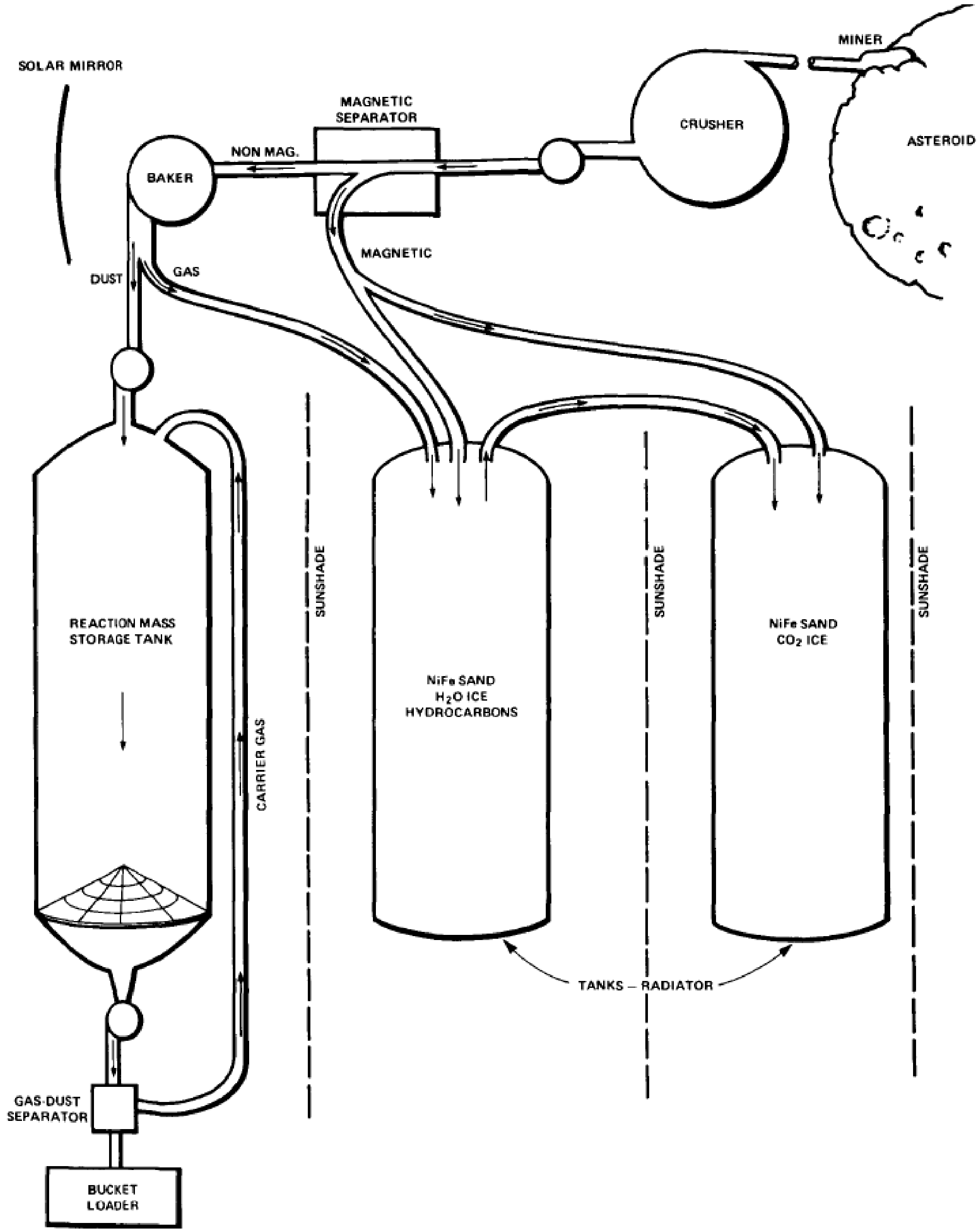


Figure A-10: Schematic Diagram of Asteroid Processor [156]

A.9 Surculus Astrum (University of Washington)

'Surculus Astrum' hails from the University of Washington Senior Design class of 2015 [144]. It is notable for the designs of a high-power electric propulsion return vehicle, and excavator boring heads in Figure A-11, with an overall architecture shown in Figure A-12. This NEO ISRU concept appears to be a one-off effort, with no follow-up from the research group observed.

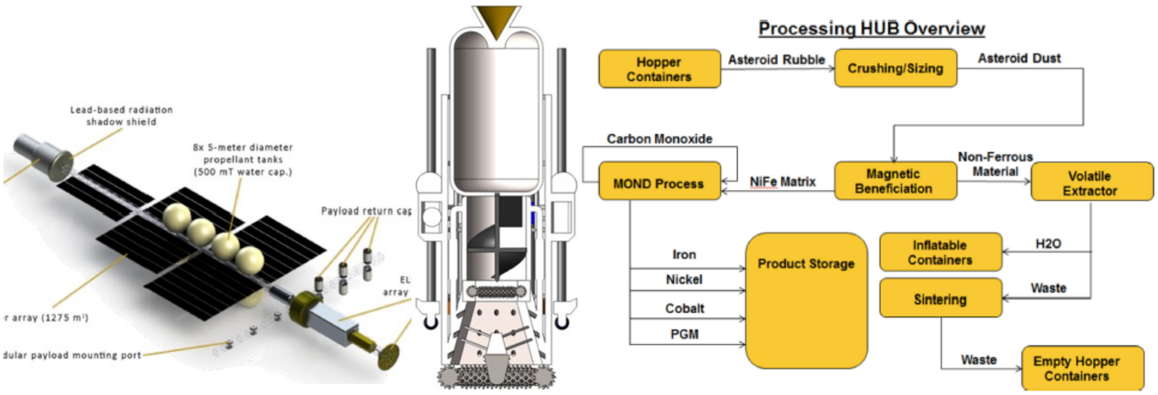


Figure A-11: Nuclear electric return vehicle, M-type asteroid boring head, and processing proposed as part of 'Surculus Astrum' [144]

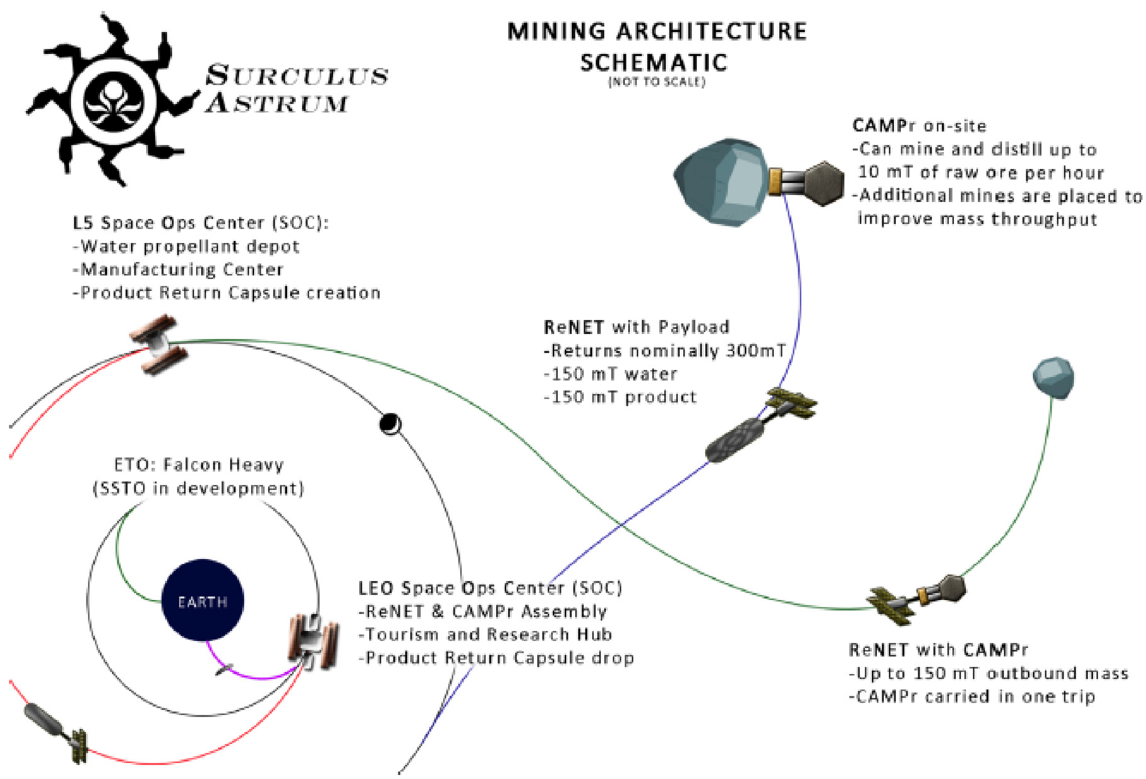


Figure A-12: University of Washington 'Surculus Astrum' NEO ISRU concept [144]

A.10 Kuck Mosquito

The drill rig proposed by Kuck is notable for being the first serious proposal for NEO ISRU, as well as an innovative extraction in place technique shown in Figure A-13 [199], [199]. Though at least three papers were published on aspects of this NEO ISRU concept development appears to have stalled, with no recent publications on the concept.

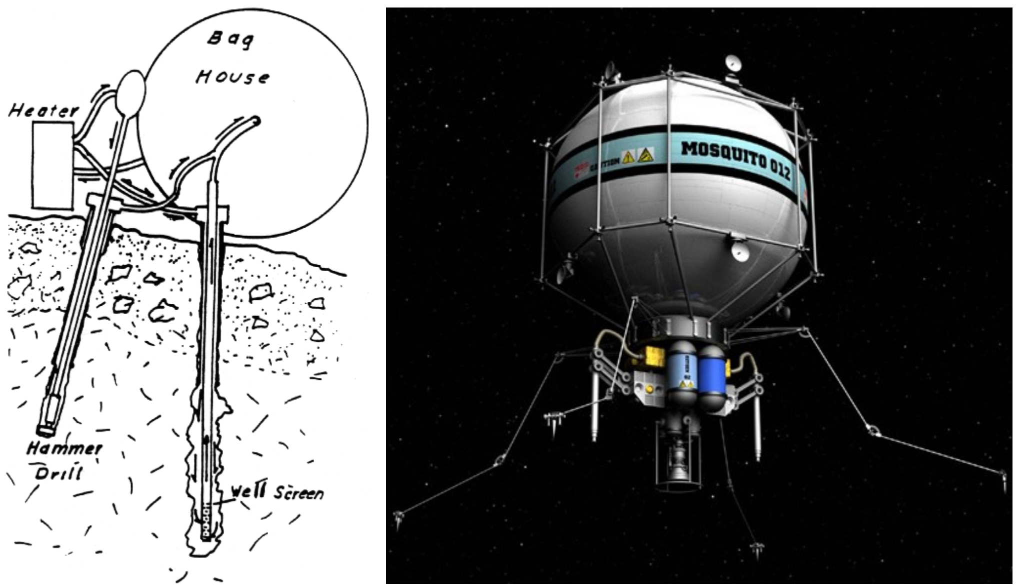


Figure A-13: Drill rig proposed by Kuck [157], with visualization (Nick Stevens)

A.11 Planetary Resources

Planetary Resources took a different tack, instead focusing public relations graphics and remote sensing techniques to detect water to build the case for increased investment in its asteroid mining efforts. Planetary resources launched an infrared imaging satellite into LEO called Arkyd-6, though its other two satellites were lost on the launch pad [142]. Their asteroid mining framework is in Figure A-14, although by most indications serious efforts did not get past the first stage of observation from afar shown. Planetary Resources was acquired by ConsenSys in 2018, and development has since halted with patents being declared open source [200], [201].

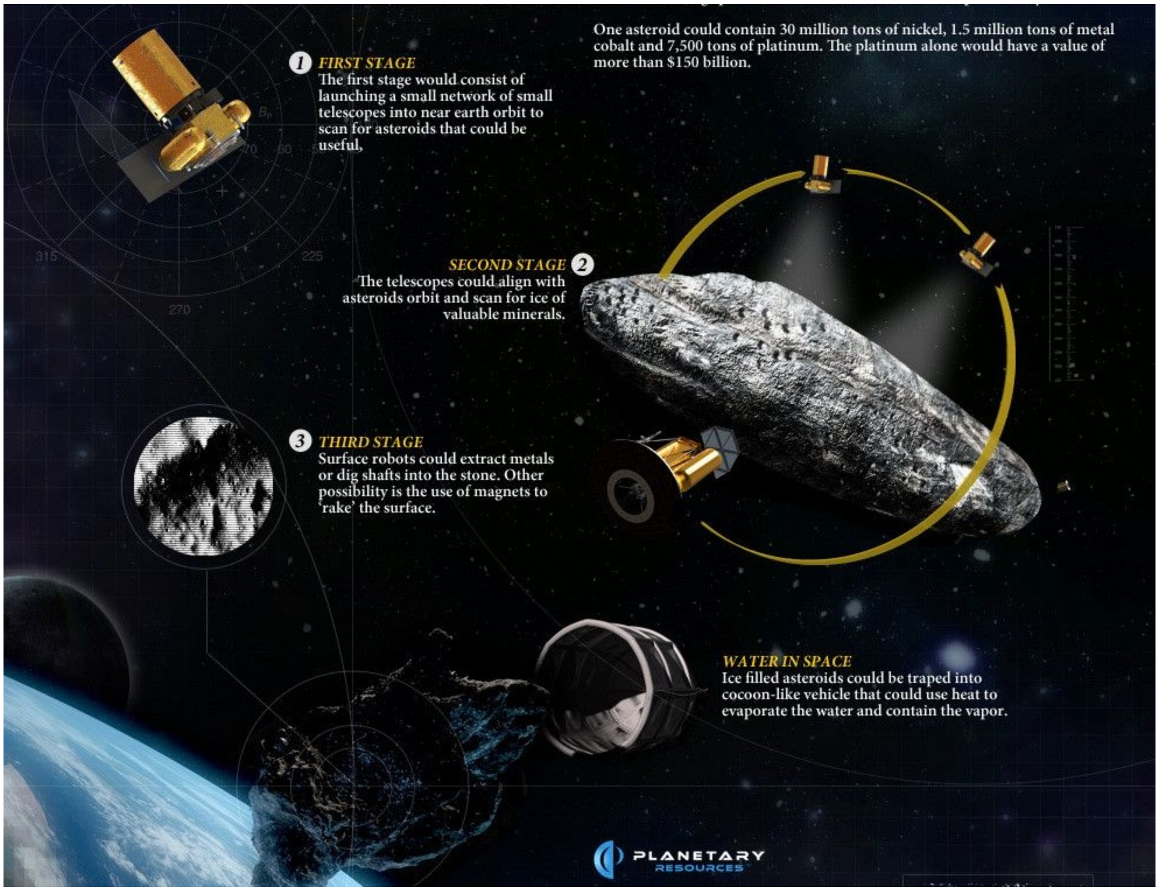


Figure A-14: Planetary Resources asteroid mining concept [202]

A.12 Carbonaceous Volatile Asteroid Recovery (Pioneer Astronautics)

The Carbonaceous Volatile Asteroid Recovery (CAVoR) system was proposed by by Pioneer Astronautics in a patent including a spreadsheet model for operation on asteroid regolith in Table A-2, thus qualifying as an NEO ISRU concept [38]. Pioneer Astronautics specializes on chemical and systems engineering for aerospace applications, with a sister company Pioneer Energy for technology transfer to the oil and gas industry [203].

Table A-2: CAVoR Reaction Mass Balance Model [38]

CAVoR Model Stream Data – 50 kg/day Asteroid Regolith Feed.

Input Data: [ ] = inputs (yellow shaded cells).

Asteroid Regolith Feed Composition:

15.00	% H2O
5.00	% organic matter
83.00	% C (dry organic matter basis)
8.65	% H (dry organic matter basis)
8.35	% O (dry organic matter basis)

Asteroid Regolith Feed Rate:

50.000	kg/day total feed rate
7.500	kg/day H2O
2.500	kg/day organic matter
10.000	kg/day H2O plus organic matter
40.000	kg/day inorganics and contaminants
n	feed pre-drying (yes "y" or no "n")

Reformer Parameters:

0.500	O2:C molar ratio
2.000	H2O:C molar ratio - minimum target
2.410	H2O:C molar ratio - actual
3.00	CO2:CO molar ratio in exhaust
100.0	CAVoR On-Stream Factor

Sabatier Parameters:

1.10	H2 inlet factor above stoichiometric
21.0	% of Sabatier exhaust CH4 recycled to reactor with permeate
5.0	vol % concentration of H2 in CH4 liquefaction feed

Summary Results:

	Stream #	1	2	3	4	5	6	7	8	9	10	11	12
	Stream ID	Asteroid Regolith Feed	Reformer Make Up Water	Water Product	Oxygen Product	Hydrogen Product	Membrane Retentate	Reformer Water and Organic Feed	Water From Feed Dryer	Reformer Exhaust	Reformer Condensate	Sabatier Hydrogen From Electrolysis	Membrane Permeate
	Average kg/day	50.000	0.000	3.208	4.020	0.000	2.790	10.000	0.000	12.555	5.166	0.828	0.849
Mass Flow Rate, kg/hr	O2				0.168								
	H2					0.000	0.001			0.020		0.035	0.005
	CO2									0.238			
	CO									0.050			
	CH4						0.115						0.115
	H2O		0.000	0.134					0.000	0.215	0.215		
	Total	2.083	0.0000	0.134	0.1675	0.000	0.116	0.417	0.000	0.523	0.215	0.035	0.120
Mass Concentration, wt %	O2				100.00					0.00			
	H2					100.00	0.66			3.80		100.00	3.89
	CO2									45.42			
	CO									3.64			
	CH4						99.34			0.00			96.11
	H2O		100.00	100.00					100.00	41.14	100.00		
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Volumetric Flow Rate, SLPM	O2				1.956								
	H2					0.000	0.142			3.687		6.397	0.067
	CO2									2.017			
	CO									0.672			
	CH4						2.689						0.715
	H2O		0.000	2.772					0.000	4.463	4.463		
	Total		0.000	2.772	1.956	0.000	2.831		0.000	10.839	4.463	6.397	1.582
Molar Concentration, vol %	O2				100.00					0.00			
	H2					100.00	5.00			34.01		100.00	54.81
	CO2									18.61			
	CO									6.20			
	CH4						95.00			0.00			45.19
	H2O		100.00	100.00					100.00	41.18	100.00		
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	Stream #	13	14	15	16	17	18	19	20	21	22	23	24
	Stream ID	Sabatier Exhaust	Sabatier Condensate	Dry Sabatier Exhaust (Membrane Feed)	Combined Water Condensate	Electrolyzer Oxygen	Reformer Oxygen	Electrolyzer Hydrogen	Reformer Feed Water	Dry Reformer Exhaust	Electrolyzer Feed Water	Recycled Hydrogen from Liquefaction	Final Methane Product
	Average kg/day	9.085	5.446	3.639	10.612	6.576	2.555	0.828	0.000	7.389	7.404	0.018	2.771
Mass Flow Rate, kg/hr	O2					0.274	0.106						
	H2	0.005		0.005				0.035		0.020		0.0000	
	CO2									0.238			
	CO									0.050			
	CH4	0.146		0.146									0.115
	H2O	0.227	0.227		0.442				0.000		0.309		
	Total	0.379	0.227	0.152	0.442	0.274	0.106	0.035	0.000	0.308	0.309	0.001	0.115
Mass Concentration, wt %	O2	0.00		0.00		100.00	100.00			0.00			
	H2	1.44		3.59				100.00		6.46		100.00	
	CO2	0.00		0.00						77.17			
	CO	0.00		0.00						16.37			
	CH4	38.61		96.41						0.00			100.00
	H2O	59.95	100.00	0.00	100.00				100.00	0.00	100.00		
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Volumetric Flow Rate, SLPM	O2					3.199	1.243						
	H2	1.008		1.008				6.397		3.687		0.142	
	CO2									2.017			
	CO									0.672			
	CH4	3.404		3.404									2.689
	H2O	4.706	4.706		3.169				0.000		6.397		
	Total	9.118	4.706	4.412	3.169	3.199	1.243	6.397	0.000	6.376	6.397	0.142	2.583
Molar Concentration, vol %	O2	0.00		0.00		100.00	100.00			0.00			
	H2	11.06		22.85				100.00		57.82		100.00	
	CO2	0.00		0.00						31.63			
	CO	0.00		0.00						10.54			
	CH4	37.33		77.15						0.00			100.00
	H2O	51.61	100.00	0.00	100.00				100.00	0.00	100.00		
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Carbon Throughput = 2.075 kg/day | Total Sabatier Feed = 14.436 SLPM | Electrolysis Power = 1.360 kilowatts

Though not explicitly stated, Table A-2 implies intended use in a fuel-rich methalox rocket engine, with a product mixture ratio of 1.46, versus a stochiometric mixture ratio of 3.99 on a mass basis. This outcome may also be due to the assumption of perfect extraction efficiency of carbon, hydrogen, and oxygen from the ore. Factoring in the extraction efficiencies computed using experimental data from heating of DSI simulants, the apparent inputs of 4.15%wt C and 2.11%wt H are equivalent to 23.6%wt C and 5.63%wt H before imperfect extraction. These boosted values violate the assumption that all carbon is released as carbon dioxide and all hydrogen is released as water, since insufficient oxygen is present in the input. It should be noted that the design for CAVoR includes a reformer module where additional oxygen and steam are injected into the ore.

A.13 Sonter (Asteroid Mining Group)

This concept is of interest due to a decent treatment of orbital transfers and economics, as well as including a limited set of functional alternatives to choose from, as shown in Figure A-15. Although published more as a work to structure the design space for NEO ISRU, Sonter offers recommendations for the ‘best near term’ solutions (circa 1997) at various points throughout the thesis that are interpreted here as a distinct concept for comparison [99]. Additional ‘initial choices’ are clarified in a research paper summarizing the work [158]. Effort spent on improving these initial choices appears to have transferred to Deep Space Industries related NEO ISRU concepts, at least before the company became defunct [103].

Engineering Choices can be identified as follows (underlines showing initial choices):

product: water; metal; gases; silicates; PGMs.

process: drilling with insitu melt and extraction; heat, dehydrate, and condense; electrostatic and magnetic extraction; carbonyl extraction.

target type: extinct or dormant comet; overtly carbonaceous or hydrous asteroid; overtly cometary; S-type asteroid; overtly metallic asteroid.

power: solar thermal; nuclear thermal; photovoltaic.

propulsion: steam rocket; mass driver; arcjet.

control: telepresence; machine autonomy; manual.

Propulsion and power choices are linked; only a subset is technically and politically viable. *In-situ propellant production at the asteroid constrains the system choices to those below:.*

Table 4 Propulsion and Power Choices

		Propulsion		
		steam rocket	arcjet	mass driver
Power	solar thermal	Yes	No	No
	solar PV	No	Yes	Yes
	nuclear	Yes (no)	Yes (no)	Yes (no)

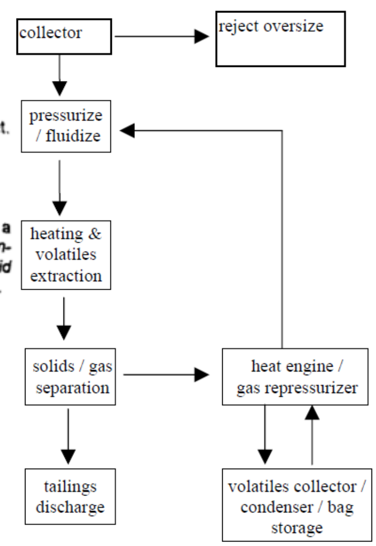


Figure A-15: A set of ‘engineering choices’ analogous to functional alternatives proposed by Sonter with ‘initial choices’ for implementation [99], [158]

This thesis is hosted on the National Space Society website, implying support for the idea being sustained within the organization in some form. Though Sonter has not published much follow-up work beyond minor updates to the thesis in 2012, this work is felt to be the spiritual successor to Sonter’s thesis. By expanding upon the options and functions Sonter proposed, this thesis takes the field a few steps further with the morphological matrix and sizing codes developed herein.

A.14 Gertsch et al. (Missouri University of Science & Technology)

Gertsch et al. proposes a schema for direct ISRU, several options for identified functions, and outlines a few concepts based upon the suspected mineralogy [80]. The set of Proposed NEO Mining and Processing Steps is discussed in § 4.1.3. Of particular interest are the concepts dealing with 'Noncohesive Friable Rock' and 'Cohesive and Hard Rock'. The former focusing on volatile refining of primitive asteroids featured a large spinning processing module tethered to a containment bag as depicted in Figure A-16 on the left, with radially successive stages of processing terminating in solar thermal thrusters for steam at the ends. The latter envisioned the use of explosive charges and/or melting of bulk regolith, then the use of centrifugal force to separate metals party shown by the clamshell in Figure A-16 on the right. These NEO ISRU concepts appears to be one-off efforts, though some of the authors are noted to be collaborating with TransAstra Corp on trajectory design and development of the extraction techniques [164], [204].

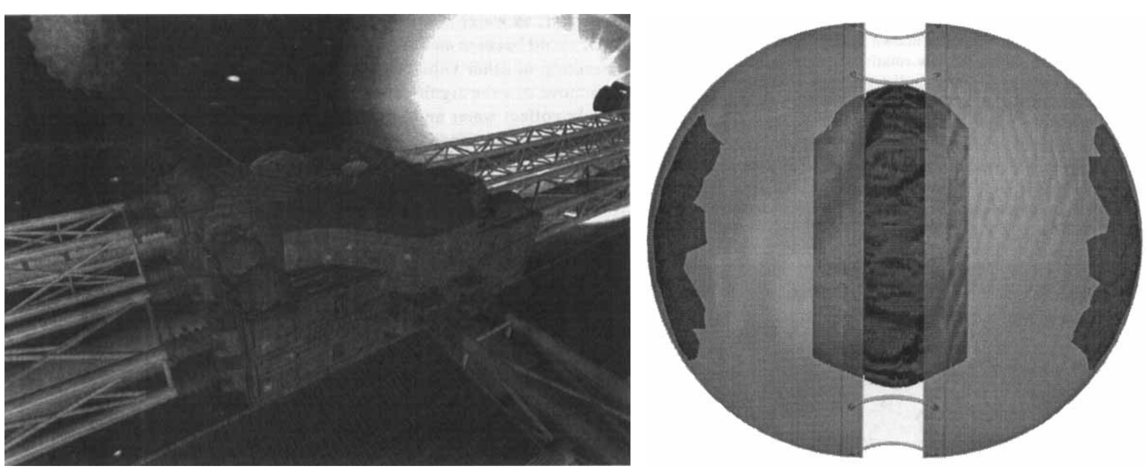


Figure A-16: Tethered processing module and 'rubblize-and-split method' [80]

A.15 Deep Space Industries

First, Deep Space Industries proposed large industrial plants to process NEO materials like in Figure A-17, then manufacture structures out of them, as in Figure A-18 [130], [205]. Their main focus as a company was ascertaining similarities of asteroid mining to terrestrial mining, and developing steam hot gas thrusters [103]. An extension of this was the desire to create regolith simulants to enable verification of prototypes, including the CI simulant described in Table 5-1 and Figure 5-10 [49], [50], [175].

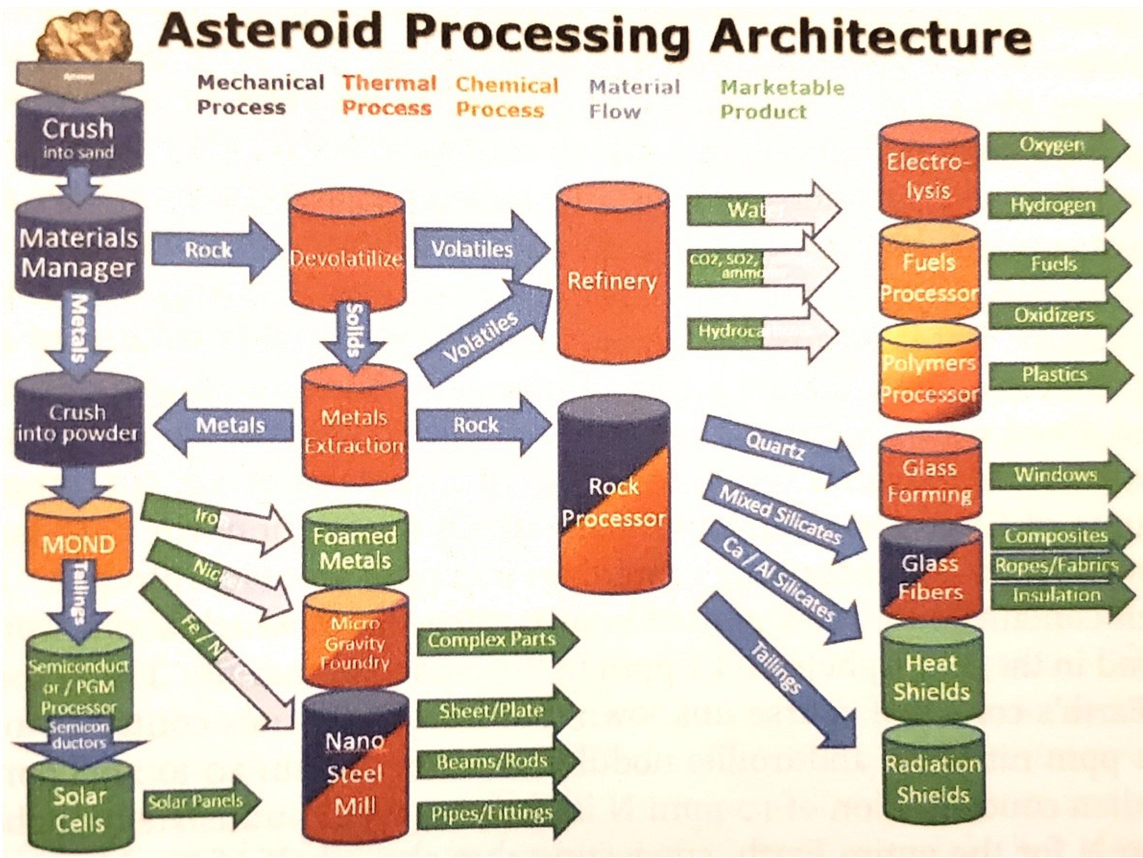


Figure A-17: Deep Space Industries asteroid processing architecture [130, p. 127]

However, Deep Space Industries was bought out by Bradford Space in early 2019 for their smallsat thruster technology [206]. Their simulant production has been absorbed by the Exolith Lab out of the University of Central Florida [173]. No news has come since.

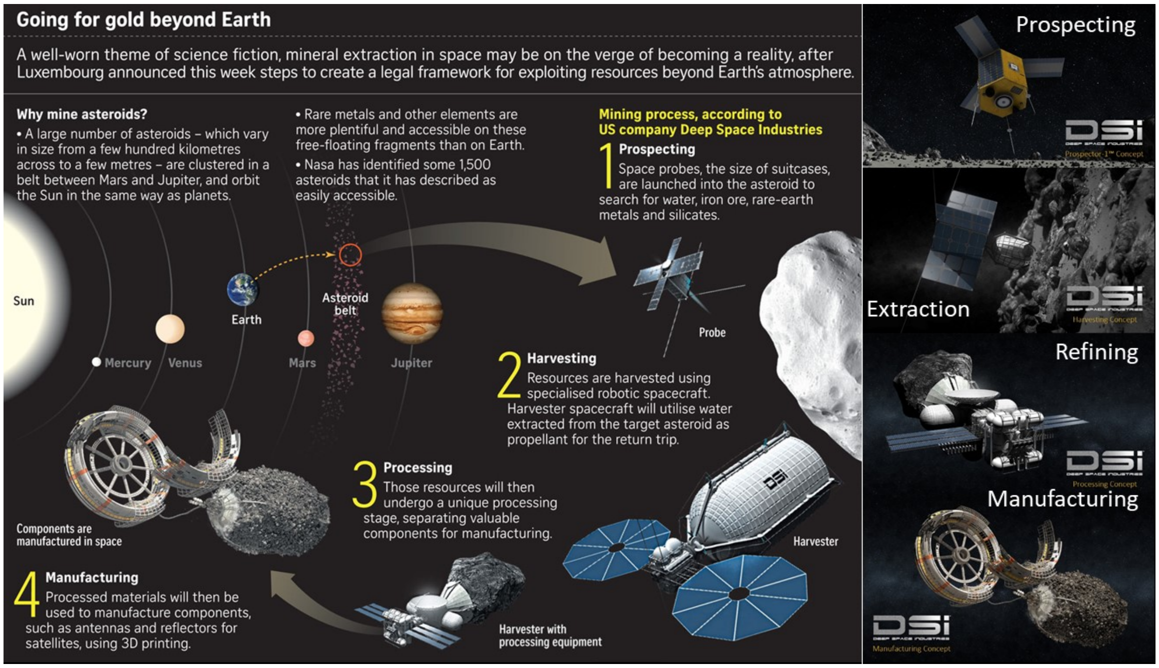
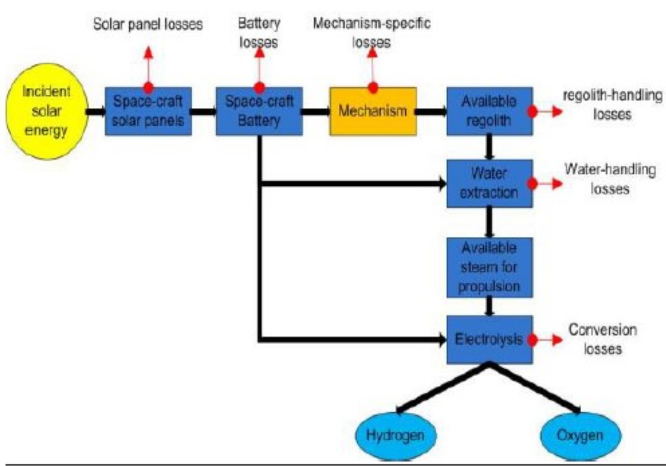


Figure A-18: Deep Space Industries asteroid mining concept (composite [205], [207])

A.16 Nallapu et al. (Arizona State)



Design Requirements	Value
Water to be extracted (Kg)	7.5
Maximum solar power (KW)	10
Surface Parameters	**Value**
Soil density (kg/m^3)	1876
Acceleration due to gravity (m/s^2)	0.0057
Cohesion (pa)	147
Specific heat of the material (J/(Kg-Celsius))	1430
Surface temperature of the material (Celsius)	200
Water extraction temperature (Celsius)	1000
Water content in the regolith (%)	10
System efficiencies	**Value**
Battery efficiency (%)	75
Solar panel efficiency (%)	29
Motor efficiency (%)	70
Drive train efficiency (%)	70
Bucket filling efficiency (%)	45
Water extraction efficiency (%)	90
Hydrogen extraction efficiency (%)	90
Oxygen extraction efficiency (%)	90

Figure A-19: Arizona State bucket wheel systems and related parameters [145].

Arizona State researchers proposed a bucket wheel design for asteroid excavation, with its involved systems and associated parameters described in Figure A-19 [145]. This concept is notable for its focus on physics-based modeling, and poising the design as an optimization problem. The models used are quite simplistic, with the exception of the bucket wheel itself. This NEO ISRU concept appears to be a one-off effort, with no follow-up from the research group observed.

A.17 Sommariva (Meta Consulting)

Sommariva proposed the beginnings of an NEO ISRU framework, though they seemed more interested in economic and policy implications for the advent of ‘asteroid mining’ [159]. The reader was deferred to Kargel for more specifics on the process, although the specifics specified were different [160]. This NEO ISRU concept appears to be a one-off effort, with no follow-up on the concept from the researcher observed.

A.18 Kargel (USGS)

Kargel focused on excavation, extraction, and refining of various metals in their concept for NEO ISRU [160]. Parallels were found between the excavation and extraction of metals when compared to available volatile options, though the metal refining steps proposed were incompatible with the selected case study. Most notable was the desire to perform multiple heating/cooling cycles for beneficiation of the product ore, as in Figure A-20. This concept appears to be a one-off effort, with minimal follow-up observed.

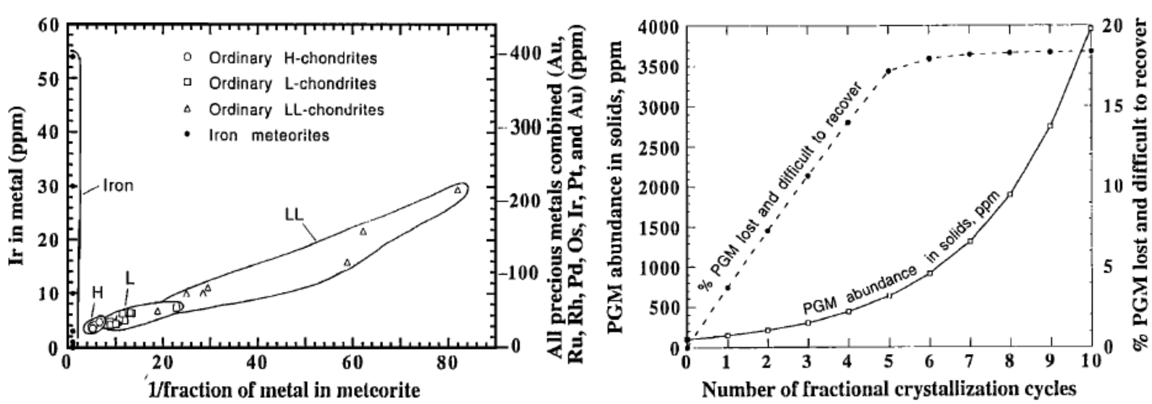


Figure A-20: Metal content of select meteorites and crystallization reheating/cooling cycles estimated to obtain a given purity of platinum group metals [160]

A.19 Benaroya (Rutgers University)

An intriguing anchoring system is proposed by Benaroya, as shown in Figure A-21 [161]. Though a limited number of other categories with options are mentioned, almost no other functional niches have selections made as a part of this concept. Therefore, this concept is an extreme example of a ‘pet project’ among ‘technology driven’ concepts.

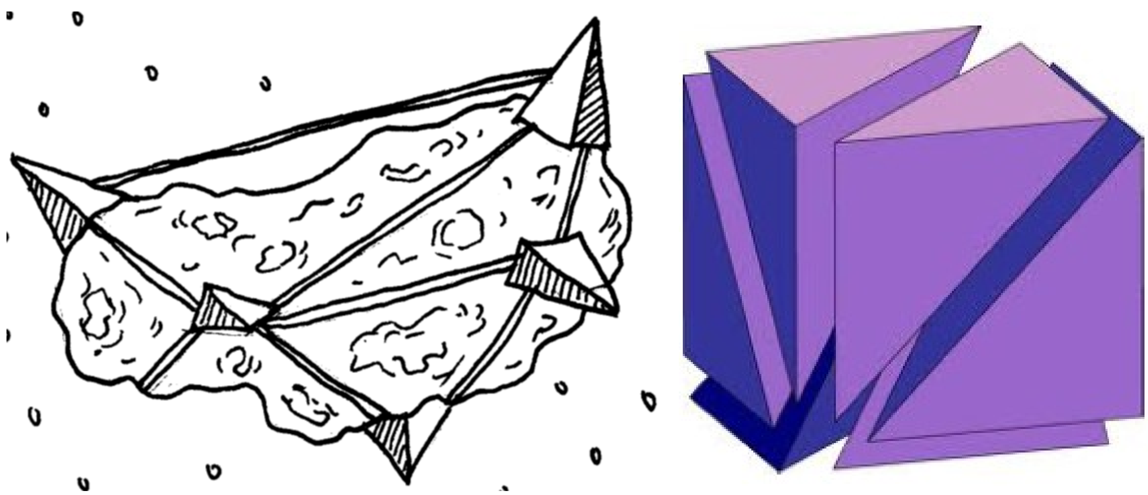


Figure A-21: Tetrahedral elements winched to an asteroid [161]

APPENDIX B. TECHNOLOGY READINESS LEVEL ASSESSMENT OF MORPHOLOGICAL OPTIONS

This appendix explains the rationale behind why different Technology Readiness Levels (TRLs) were assigned to different morphological options. Its structure parallels the morphological matrix displaying microgravity (Table 4-5) and terrestrial (Table 4-6) TRLs. Headings correspond to types (e.g. § B.2 – Direct ISRU), groups (e.g. § B.2.2 – Excavation), and categories (e.g. § B.2.2.2 – Heating [Primary]), with each morphological option given its own paragraph. Terms are in **boldface** when being defined herein. TRL definitions in Table B-1 stem from DOD practices as represented in GAO-16-410G [112].

The primary goal of this streamlined Technology Readiness Assessment (TRA) was to ascertain how feasible an identified option is for implementation, by means of identifying a functioning system or one under development. The goal here is to gauge the available capabilities within a broad design space, in order to systematically down select morphological options. Due to time constraints, the use of phenomenological inference upon available sources was conducted, instead of other methods such as surveying subject matter experts or checklists of necessary capabilities. To these ends, a type example for each morphological option was sought for both terrestrial and microgravity applications, in order to roughly characterize the TRL of the morphological option in accordance with Table B-1. Terrestrial applications are considered to be those within Earth's gravity well or observing Earth's surface. Microgravity applications include orbital and deep space systems, with the exception of those operating after landing on a celestial body with a significant gravity well. Further explanation on methods is in § 4.4.1.

Table B-1: Technological Readiness Levels (TRL), as per GAO-16-410G [112]

Technology readiness level (TRL)	Description
1 **Basic principles observed and reported**	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
2 **Technology concept and/or application formulated**	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3 **Analytical and experimental critical function and/or characteristic proof of concept**	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4 **Component and/or breadboard validation in laboratory environment**	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.
5 **Component and/or breadboard validation in relevant environment**	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
6 **System/subsystem model or prototype demonstration in a relevant environment**	Representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7 **System prototype demonstration in an operational environment**	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
8 **Actual system completed and qualified through test and demonstration**	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9 **Actual system proven through successful mission operations**	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Note that while this analysis is focused upon technological readiness for NEO applications, other parties may wish to use the outlined TRLs for other applications. It is the author's opinion that these TRLs directly apply to orbital servicing and manufacturing on orbit due to commonalities in the service environment. More careful study is merited before extrapolating to Lunar and Martian ISRU applications though. It is the author's opinion that equivalent TRL will generally be equal to or greater than the one expressed here, though several exceptions due to incompatibilities exist (e.g. synched bag containment). Surface and microgravity ISRU applications are felt to materially diverge in development above TRL 4, with many systems developed for surface applications de-rated for inclusion herein. Regardless, more in depth studies are still recommended, as capabilities degrade over time, and accuracy to ground truth may vary.

Since this is not a comprehensive assessment, the reader should note that the TRLs presented here are a rough approximation at best. Each morphological option is likely to have a plethora of ideas that fall under its definition, but only one can be described as the 'type example' for characterization. This search was also conducted entirely in the public domain by scouring the internet for scholarly sources and capabilities of businesses. It is entirely possible that the assessed technologies are farther along in classified or proprietary use cases meriting a higher TRL, or have been depreciated or discontinued meriting a lower TRL, without the author's knowledge. Note that TRLs decrease over time without active use, and even 'flight proven' technologies could merit a lower TRL if documentation is insufficient and/or the supply chain has been repurposed. This work tries to keep type examples to a time horizon within the last decade (2009 – 2019), though this is not always possible. Please keep in mind the limitations of this approach when using this information.

B.1 Sample Return

The **sample return** 'type' captures the aspects of the selected mission that are not captured by the subsequent 'groups' relating to In-Situ Resource Utilization (ISRU). The main aspects considered here are the degree of integration of the System of Systems (SoS), and the characteristics of the return vehicle that influence the propellant mass required.

B.1.1 Integration

Integration is used here to refer to the modularity and adaptability of the SoS. **Separation** refers to the physical detachment permitted between systems in the SoS. **Redundancy** refers to how the risk of subsystem failure is mitigated in the design. Note that an operational unit is a spacecraft capable or preforming one or many of the tasks identified elsewhere in this functional decomposition. To simplify matters, the level of separation & redundancy selected are assumed to be fully consistent across all systems in the SoS for modeling purposes.

<u>B.1.1.1 Separation</u>

Single Unit (None) refers to the use of a single spacecraft that has all of the equipment on-board or mounted to it to perform the necessary tasks for the SoS NEO ISPP. Note that a single lander with a single deployed orbiter for prospecting and/or long range communications still falls into this category, but not if multiple daughter craft are deployed. Microgravity TRL 9 is assumed based upon case studies in *New SMAD* [137].

Detachable Modules refers to the use of a modular architecture of systems with shared interfaces, which combine to form a small number of operational unit(s). Note that this also includes a primary spacecraft with a small number of daughter craft deployed. Microgravity TRL 9 is assumed based upon case studies in *New SMAD* [137].

Subsequent Missions refers to the progressive deployment of additional processing equipment to the NEO over time. One such example would be sending prospecting spacecraft to one or more NEO ahead of time to establish if the required feedstock exists, then sending the remaining processing equipment along latter if positive results are seen.

Note that for the purposes of modelling, only the total mass of the SoS deployed to the NEO is considered, irrespective of when its arrived. Microgravity TRL 9 is assumed based upon case studies in *New SMAD* [137].

Swarming Craft refers to the use of a large number of indivisible operational units working together to perform the necessary tasks for the SoS NEO ISPP.

B.1.1.2 Redundancy

Single String (None) refers to the use of a SoS that only has one set of hardware to accomplish the task at hand, with no backups [137]. This definition includes design to encourage 'aging gracefully' by means of reduced performance instead of failure. In this case, a single disruption could take out the entire SoS or unacceptably degrade performance, though the resulting spacecraft would be lower mass and potentially have a lower lifecycle cost. Single string spacecraft such as NASA's Wide-field Infrared Survey Explorer have flown in earth orbit, meriting terrestrial TRL 9. Planetary missions such as NASA's Lunar Reconnaissance Orbiter have also utilized single string configurations, meriting microgravity TRL 9 as well.

Independent Strings or block redundancy refers to the use of several isolated systems to deliver a capability [137]. Note that a primary system and an idle backup can be used, or the extra systems can be run in parallel at reduced capacity. Cross-checking results from multiple computer cores or blind studies is also considered here due to the isolation of components while they are operating. Microgravity TRL 9 is assumed based upon case studies in *New SMAD* [137].

Cross-Strapped Strings refers to non-isolated redundant systems with interchangeable subsystems that can be swapped into operation as needed [137]. Note that this can include intelligently balancing capacity utilization, or routing flows around malfunctioning components. Microgravity TRL 9 is assumed based upon case studies in *New SMAD* [137].

Multiple Craft refers to the use of multiple largely identical operational units that are independently mobile to perform the task at hand. These distinct units need not have single string operation themselves, nor be all sent at once as part of the same mission. Note that for the purposes of modelling, only the total mass of the SoS deployed to the NEO is considered, irrespective of when it arrives or how many parts it is separated into.

B.1.2 Return Vehicle

The **Return Vehicle** refers to a spacecraft that is designed to transport NEO regolith samples from the NEO back to Low Earth Orbit (LEO). The two main inputs about the return vehicle needed to size the In-Situ Propellant Production (ISPP) is the type of propellant and the mass of propellant required for the journey. Only propellants that can be produced from NEO resources are considered, excluding noble gasses and most types of electric propulsion. Mass drivers are not considered due to space debris concerns.

In this group, the terrestrial analogs considered are orbital launch vehicles and crew capsules that return from LEO. **Propulsion** refers to the principal method used to accelerate the return vehicle by providing thrust. **Propellant** refers to the choice of which substance is ejected at high velocity from the spacecraft to provide thrust. **Chamber Reaction** is used to specify the stoichiometry of the rocket engine reaction. Lastly, **Return Type** describes how much of the SoS NEO ISPP is returned to LEO; this acts as a rough estimate of the empty weight. There is an intrinsic trade off here between expending systems for higher performance, and holding on to systems to facilitate easier reuse.

B.1.2.1 Propulsion

Chemical Reaction (liquid) rocket engine is defined here as a set of materials that combust to pressurize a fluid, which is ejected out a nozzle in turn. Note that only simple liquid bipropellants are considered in this work, as complex chemistries are not typically considered for in-situ propellant production (ISPP) due to increased processing complexity and lower performance versus hydrolox. Solid rocket motors are excluded as well due to their complex chemistries. The first stage of the Ariane 5 uses a sea level hydrolox rocket engine, meriting terrestrial TRL 9 [208]. The Mitsubishi Heavy Industries H-IIA second stage uses a vacuum nozzle burning hydrolox, meriting microgravity TRL 9 [209].

Solar Thermal thruster is defined here as the use of radiant solar energy to impart thermal energy to pressurize a fluid, which is ejected out a nozzle in turn. A prototype solar thermal system has been tested outside by Physical Sciences Corporation, meriting microgravity TRL 4 [210]. Analytical studies have also been performed for vacuum systems by TransAstra Corp. [89]. Note that thrust to weight levels and bulk of the solar concentrator system are not conducive for an orbital launch vehicle.

Nuclear Thermal thruster is defined here as the use of a nuclear reactor to produce heat which is then imparted onto propellant before ejecting the propellant out of a nozzle. Note that both fission and fusion reactors are included. NASA's Nuclear Engine for Rocket Vehicle Application (NERVA) is an example of the fission type with successful ground test firings in the early 1970's. Due to the passage of time and lack of subsequent testing, it is felt that the microgravity TRL has been de-rated to TRL 4. Note that thrust to weight levels are not thought to be conducive for an orbital launch vehicle.

Electrothermal thruster is defined here as the use of using internal spacecraft power to impart thermal energy into a fluid to pressurize it, then ejected out a nozzle in turn. This power can be imparted by means of an electrical resistance heater, or a source of electromagnetic radiation such as a microwave emitter. Surrey Satellite Technology Ltd. has tested an electric 'water resistojet' propulsion system in space on their UK-MDC-1 satellite [211]. Momentus Space has also successfully conducted an on-orbit test of their microwave powered 'water plasma' propulsion on their El Camino Real CubeSat, meriting microgravity TRL 6 [212]. Note that the thrust to weight levels of the electric thermal propulsion systems are not conducive for an orbital launch vehicle, especially when the electric generator power plant mass is included.

Electromagnetic thrusters utilize the Lorentz force or electric fields not aligned with the resultant thrust direction to accelerate ions away from the spacecraft. Due to the availability of commercial electrodeless Lorenz force thrusters for satellites, microgravity TRL 9 is assumed. Note that thrust to weight levels are not thought to be conducive for an orbital launch vehicle.

Ion Thruster is defined here as the use of electric fields aligned with the direction of thrust to accelerate ions away from the spacecraft. Due to the availability of commercial hall thrusters for satellites, microgravity TRL 9 is assumed. Note that thrust to weight levels are not thought to be conducive for an orbital launch vehicle.

B.1.2.2 Propellant

Steam Monopropellant or water is defined here as heated water that is ejected out a nozzle for the purpose of providing thrust. Note that the fluid can undergo thermal decomposition at elevated temperatures, and will often transition from a liquid in the holding tank into a gas. On Earth, this technology has been used to give one-off custom motorcycles an extra burst of speed, meriting terrestrial TRL 7 [213]. In orbit, Surrey Satellite Technology Ltd. has tested an electric thermal steam propulsion system on their UK-MDC-1 satellite, meriting microgravity TRL 6 [211]. The Deep Space Industries Comet Thruster (now part of Bradford Space) is another steam electric system that has undergone testing [214].

Hydrogen is defined here as atomic hydrogen gas or ionized protons that are is ejected out a nozzle for the purpose of providing thrust. Ground tests using hydrogen for propellant in Ad Astra's Variable Specific Impulse Magnetoplasma Rocket (VASIMR), thus meriting microgravity TRL 4 for proof of concept tests [178], [179]. Note that thrust to weight levels are not thought to be conducive for an orbital launch vehicle.

Hydrolox is a chemical bipropellant with hydrogen as the fuel and oxygen as the oxidizer. Hydrolox is widely noted as the most efficient chemical propellant, due to having the lowest average molecular weight. The first stage of the Ariane 5 uses a sea level hydrolox rocket engine, meriting terrestrial TRL 9 [208]. The second stage of the Mitsubishi Heavy Industries H-IIA uses a vacuum hydrolox rocket engine, meriting microgravity TRL 9 [209].

Methalox is a chemical bipropellant with methane as the fuel and oxygen as the oxidizer. Although methalox rockets have not yet entered into orbit, there has been a surge of recent research and development effort into methalox rocket engines [215]. This is due to the lower cost of natural gas feedstocks versus kerosene for fuel (e.g. SpaceX and Blue Origin), and lesser dependence on finding water deposits for in-situ propellant production versus hydrolox and steam monopropellant (NASA Mars Sample Return). The SpaceX Raptor rocket engine is currently the methalox rocket engine furthest along in its development, to public knowledge. The sea level version of Raptor was recently flight tested by SpaceX on an ad-hoc test vehicle named Starhopper, thus meriting terrestrial TRL 5 [216]. As no public information has yet been released by SpaceX on testing of a Raptor vacuum variant, it is presumed to have existent analytical modeling worthy of microgravity TRL 3 but lack hardware prototypes meriting increased technological readiness.

B.1.2.3 Chamber Reaction

Fuel Rich means that excess fuel beyond the stoichiometric reaction mixture ratio is injected into the rocket engine. This is typically done when the fuel has a lower molecular mass than the equivalent amount of oxidizer to fully combust it, in order to increase the average thrust velocity and improve the rocket engine specific impulse [60]. Hydrolox engines have the highest specific impulse around an oxidizer to fuel mass ratio of around 3.5, but are typically run around 5-6 to reduce tankage volume and mass [217]. The first stage of the Ariane 5 uses a sea level hydrolox rocket engine, meriting terrestrial TRL 9 [208]. The second stage of the Mitsubishi Heavy Industries H-IIA uses a vacuum hydrolox rocket engine, meriting microgravity TRL 9 [209].

Stoichiometric chamber reaction means that a mixture ratio for complete combustion of fuel and oxidizer is used within the rocket engine. The main advantage of using a stoichiometric reaction for rocket engines supplied using in-situ propellant production (ISPP) is an increased utilization of the propellant produced, which has the potential to reduce the mass of the SoS ISPP required to produce the same propellant mass. When off-stoichiometric ratios are used by the engine (e.g. MR = 5.5 for hydrolox instead of stoichiometric MR = 8), a significant imbalance in the amount of fuel and oxidizer is required manifests [60]. Since the same resource (e.g. water) is used to produce the fuel and the oxidizer, this translates into overproduction of either the fuel or the oxidizer onsite; normally excess oxygen is produced as the bipropellants considered here are run fuel rich. The downside of using stoichiometric reactions for thrust is a reduction in specific impulse, which leads to a greater overall mass of propellant required. This is an additional consideration that should be considered when selecting the mixture ratio to be used for ISPP. Although there are currently no known liquid rocket engines that are designed to run with a stoichiometric mixture ratio, it is believed that the theoretical framework and procedures for development and operation are already well established from other liquid rocket engines. Thus, it is felt that terrestrial and microgravity TRL 9 is merited.

Oxidizer Rich means that excess oxidizer beyond the stoichiometric reaction mixture ratio is injected into the rocket engine. This is done for a full engine when the oxidizer has a lower molecular mass than the equivalent amount of fuel to fully combust it, in order to increase the average thrust velocity and improve the rocket engine specific impulse [60]. An additional, more common use case is the use of oxidizer rich combustion is a pre-burner in a staged combustion cycle, used to power the turbopumps that feed the rocket engine [218]. The NPO Energomash RD-180 powering the ULA Atlas V uses an oxidizer rich pre-burner, as well as the SpaceX Raptor engine currently under development [215], [219]. Since specialized materials and procedures have been developed and proven on the test stand, but not integrated with a specifically designed full expansion nozzle, it is felt that terrestrial TRL 5 is merited. For deep space applications, authorities have noted that significantly greater quantities of oxygen and metals are available on the lunar surface than organic elements (like hydrogen and carbon) [220]. Powdered aluminum hybrid rocket engines have been proposed to take advantage of this, with some preliminary testing done many moons ago [221]. Since the theoretical concepts exist but relatively little active research has been done recently, microgravity TRL 3 is felt to be merited.

N/A: A null option (**N/A**) is permissible here, since not all propulsion types require a chemical reaction to occur. Note that ionization and thermal decomposition are not counted as chemical reactions for the purposes of this morphological category. Most electric spacecraft propulsion types are included here, along with solar & nuclear thermal.

B.1.2.4 Return Type

Whole SoS refers to a concept where all of the systems within the systems of systems (SoS) sent have the capability to be returned together at the end of the mission, excepting consumables used throughout the mission. These SoS concepts are generally fully reusable, without expending or leaving behind any systems. While this is the typical mode of operation for terrestrial vehicles like automobiles and passenger aircraft, the performance limits imposed by the rocket equation (1) in terms of energy and mass penalties typically precludes their use. Single stage to orbit launch vehicles have long been a dream of the spaceflight community; the X-33 VentureStar came the closest to reality, with a partially integrated test vehicle meriting terrestrial TRL 5 [222].

In a microgravity environment, using the whole SoS for the return trip implies that the systems are tightly integrated into the same spacecraft bus, and/or repackaged for the return trip. This has the advantage of simplifying the mission design at the expense of critical failure modes from collocated equipment and increased integration difficulty. However, the empty mass of the craft returned from the NEO increases significantly, requiring more propellant for the same Δv, thus requiring upsizing of ISPP in an iterative loop. This option also precludes additional spacecraft from visiting the NEO to refuel after the primary mission, although redeployment to a new NEO target after payload delivery and refueling becomes an option. A few concepts of this nature have been proposed, with the HoneyBee Robotics the World Is Not Enough demonstrator being the sole example found that was prototyped as integrated hardware, thus meriting microgravity TRL 4 [223].

Partial / Some Systems refers to a concept where some of the systems within the SoS are left behind or otherwise discarded after a single use. These SoS concepts are generally capable of partial reuse. For orbital launch systems, the best example of this are the SpaceX cargo resupply missions to the ISS. For SpaceX CRS-13 both the pressurized portion of the Dragon capsule and the first stage of the Falcon 9 launch vehicle were reused from a previous mission and recovered again after use, meriting terrestrial TRL 9 [224]. When it comes to deep space operations though, the only available examples were paper studies. Notable here is the TransAstra Honey Bee, which proposes using a single use inflatable bag to encapsulate the NEO; this back appears to be detached from the SoS upon returning to LEO, with a replacement installed after the payload is delivered [89]. The well-developed analytical nature of this concept merits microgravity TRL 3, due to the lack of integrated prototypes. Note that this concept is poised to rapidly advance to TRL 6, with the recent award of a NIAC Phase III contract for further development and integration of the 'Mini Bee™' concept concluding in ground test [66], [96], [165].

Return Vehicles refers to a concept where one or more specialized system(s) within a SoS are specifically designed to return a payload, with the rest of the systems left behind or otherwise discarded after a single use. Note that this option includes conventional fully expendable space vehicles, as well as permitting fully reusable architectures that are specialized into 'propellant depot' infrastructure and 'space tug' transfer vehicles. The main difference betwixt these options is standardization of interfaces and extension of mission life. In this way the return vehicle is capable of being refueled and sent to another destination, while the direct and indirect ISPP systems are still active after the primary mission has ended and capable of refueling other transfer vehicles that dock with it with propellant.

This is a fantastic vision, but the demonstrated capabilities found in the literature are primarily of the expendable, single use variety. These vehicles tend to use an in-space propulsion system that is used to travel to a destination and also to return from it, with a dedicated subsection of the vehicle designed to reenter the atmosphere. Of orbital launch vehicles, a good example of a return vehicle is the Roscosmos Soyuz; modernization efforts over the years such as the newest Soyuz MS variant indicate knowledge has been retained, meriting terrestrial TRL 9 [225]. For deep space missions, the JAXA Hayabusa mission to S-type Itokawa is a good example of the type; the spacecraft traveled to and from the NEO using ion engines, and released a reentry capsule upon return for sample recovery [120].

Follow-up missions using similar techniques, such as JAXA Hayabusa 2, indicate the retention of design knowledge over the years meriting microgravity TRL 9 [79].

B.2 Direct ISRU

Direct ISRU is defined here is the means by which a sequence of events for the processing of space resources is enacted. As per the functional decomposition in § 4.2: Functional Decomposition, the following key functions have been identified: prospecting for resources, excavation of ore, extraction of resources from ore, refining of resources into a consumables, storage of the consumables, and material handling throughout. Here the resource is defined as the substance of value (e.g. water). The ore is the naturally occurring form of the resource. The consumable is the processed and purified form of the resource ready for use by other systems.

B.2.1 Prospecting

Prospecting is defined here as discerning the location of 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, especially as part of local observation. **Sampling** refers to methods of disturbing NEO regolith to ascertain its properties. Note that a prospecting system tends to have multiple types of instrument packages involved in local observation though only category is shown to simplify the morphological matrix.

B.2.1.1 Local Observations

Passive Observation here means observing electromagnetic radiation coming from the direction of a celestial body while in orbit of the same celestial body. Monitoring from afar is excluded from this definition, since signal quality degrades as noise increases with distance and only equipment delivered to the vicinity of the NEO has a direct impact on the SoS NEO ISPP mass estimate. In Earth orbit, civilian remote sensing satellites and military intelligence, surveillance and reconnaissance orbital platforms have widespread use for analogous applications of Earth observation. Thus, terrestrial TRL 9 is merited. Similar techniques have been used on sampling missions to NEO, such as spectral analysis on the NASA Deep Impact mission to comet Tempel 1, meriting microgravity TRL 9 [226].

Active Observation here means emitting electromagnetic radiation and then observing how it bounces off of a celestial body while in orbit of the same celestial body. Both LiDAR and radar systems are active remote sensing systems, by definition. An example terrestrial use for these active orbital systems is polar ice sheet monitoring; the ESA CryoSat uses radar altimetry, while the NASA CALIPSO uses LiDAR for this purpose [227], [228]. This merits terrestrial TRL 9. The JAXA Hayabusa mission to S-type 25143 Itokawa included a LiDAR system which was used for navigation and surface characterization, meriting microgravity TRL 9 [229].

Seismic Survey here means the use of mechanical waves within a medium to determine the internal structure of a body. Within the oil and gas industry on Earth, compressed air is used as an acoustic source underwater while vibrator trucks are used on land; thus meriting terrestrial TRL 9 [230], [231]. Apollo 15 introduced seismic techniques on Luna, with the Apollo Passive Seismic Experiment monitoring for impacts upon the lunar surface [232]. These techniques were refined and successfully used in the ESA Rosetta mission, in the Cometary Acoustic Surface Sounding Experiment (CASSE) in the feet of the Philae Lander which enabled the Surface Electric Sounding and Acoustic Monitoring Experiment (SESAME) [233]. Both passive and active methods were used to generate data that was transmitted back to Earth, meriting microgravity TRL 9.

Orbital Gravimetry is defined here as inferring characteristics about the mass distribution of a body from careful observation of bodies orbiting it. Satellite geodesy and related methods are included in this category. Missions such as the joint NASA-DLR Gravity Recovery and Climate Experiment (GRACE) and its successor mapped the Earth's gravity field on a monthly basis, using a pair of satellites with a K-band microwave ranging system to ascertain orbital variations [234]. This and other efforts merit terrestrial TRL 9. Similar techniques have also been used by the NASA OSIRIS-REx mission to analyze the composition of 101955 Bennu, through the study of the trajectories for particles ejected from its surface [185], [235]. These promising developments for a mission in progress are felt to merit microgravity TRL 8.

B.2.1.2 Wave Type

Far Infrared / Thermal imaging refers to electromagnetic wavelengths typically used to observe thermal radiation emitted due to Brownian motion; wavelengths of 50 μm to 1 mm are typical in industry (ISO 20473:2007). On earth, thermal imaging solutions are commonly used as a type of COTS security camera, meriting terrestrial TRL 9 [236]. In space both Voyager 1 and 2 carried a far infrared camera, but one has not been deployed to a NEO until NASA's OSIRIS-REx mission currently in progress, thus meriting microgravity TRL 8 [237], [238].

Near Infrared imaging here refers to electromagnetic wavelengths used to discern whether water or hydrated minerals are present in a NEO; wavelengths of 0.7 μm to 5 μm are typical in astronomy. The main absorption bands of the water molecule (H_2O) are typically noted in the vicinity of 3.1 μm, and absorption by hydroxyl groups (-OH) in water and hydrated molecules near 0.7 μm [117], [239]. Near infrared cameras are commonly used as COTS security cameras on Earth in low lighting conditions, meriting terrestrial TRL 9 [240]. The Visible and Infrared Thermal Imaging Spectrometer (VITIS) onboard the ESA Rosetta spacecraft had three channels covering 0.2 μm to 5 μm, thus meriting microgravity TRL 9 [241].

Visible Light is the use of electromagnetic wavelengths typically considered visible to the human eye; wavelengths of 0.4 μm to 0.7 μm are considered here. On Earth digital cameras for visual light have proliferated, on COTS devices ranging from lightweight smartphone chipsets to telephoto photography; this merits terrestrial TRL 9. Similarly, most spacecraft traveling into deep space typically have visual light cameras to transmit pictures back to Earth; one example is the ESA Rosetta VITIS that covered 0.2 μm to 5 μm, thus meriting microgravity TRL 9 [241].

Radar here is an active orbital method using microwaves to investigate features on a celestial body; wavelengths of 3 mm to 1.5 m are considered here [242]. In earth orbit, spacecraft such as the ESA CryoSat use radar altimetry to measure the ice sheet height, thus meriting terrestrial TRL 9 [228]. The ESA Comet Nucleus Sounding Experiment by

Radiowave Transmission (CONSERT) used microwaves transmitted by the Rosetta orbiter and received by the Philae lander to characterize the interior of comet 67P Churyumov–Gerasimenko; thus meriting microgravity TRL 9 [243].

Sound / Mechanical means the use of mechanical waves within a medium here. As the vacuum of space is generally considered too sparsely populated for particles to frequently collide, this medium is restricted to the solid mass of the NEO itself. On Earth passive sound observation is used in seismology to detect earthquakes, while active broadcasts are generally used to explore for oil and gas deposits; this merits terrestrial TRL 9 [230], [231]. Seismic reflection and refraction techniques can both be used to determine interior composition changes whether the seismic source is generated naturally (passive) or by a related system (active). Both approaches were used during the ESA Rosetta mission for the Surface Electric Sounding and Acoustic Monitoring Experiment (SESAME), thus meriting TRL 9 [134].

Subatomic Particle is defined here to be the discernment of variability in the detection of elementary particles of matter or atomic building blocks. Note that the detection of neutrons, neutrinos, and/or solar wind in some cases are all included in this category.

N/A: A null option (**N/A**) is permissible here, since prospecting techniques exist that do not require the observation of electromagnetic nor mechanical waves. If a sampling method using kinetic penetrators or excavation is selected, the null option for wave type is valid. Do note that remote sensing, seismic surveys and sampling are complementary, so it is unlikely an SoS NEO ISPP will be fielded without some form of wave observation. All null options have terrestrial TRL 9 and microgravity TRL 9 by default, the highest value.

B.2.1.3 Sampling

Kinetic Penetrator (smart) is defined here as a projectile with internal sensors designed to embed itself in a body, where data is recorded and transmitted after the projectile has stopped. The closest analog on Earth is a bunker buster bomb, with a fuse triggering an explosion after impact, though no data is recorded by the device. The closest civilian analog available is a geophysical sensing beacon penetrator, though the only public information available is in the form of a patent [244]. Thus, this technology is rated at terrestrial TRL 1. Some designs for a kinetic penetrator for spacecraft have been advanced for sending a probe to Europa, as well as ‘water liberation experiments’ after impact into NEO [142], [245], [246]. However, only impactor designs have been presented in unclassified sources with neither electronics nor shapes that can survive the impacts demonstrated, thus meriting TRL 2 [245].

Impactor (dumb) is defined as the release of energy by having a body colliding with a target body for subsequent observation. This observation can be seismic waves generated by the impact itself, and/or the ejecta plume emanating from the impact site. In the field of seismology, one way to generate a seismic source is to fire a specialized gun directly into the ground, thus meriting terrestrial TRL 9 [247]. The NASA Deep Impact mission used a similar principle, where a flyby observer spacecraft watched as a specially designed impactor spacecraft hit comet 9P Tempel 1 shortly beforehand; the success of this mission merits microgravity TRL 9 [226]. Note that sensors can exist on an impactor to gather data before impact, though these sensor are not designed to survive the collision.

Excavate (automated) is defined as removing a sample of material from a body to perform analysis upon it in the field. Any method of The ESA Rosetta mission deployed the Philae lander which did just this, recording in-situ comet composition results of comet 67P Churyumov–Gerasimenko, meriting microgravity TRL 9 [248]. The closest terrestrial analog appears to be experimental work to characterize soil properties during excavation by earthmovers, with some experimental results, thus meriting terrestrial TRL 3 [249].

Touch & Go (TAGSAM) is a category of tools that require only a short period of contact with a body to acquire a sample of said body. The category is based off of the NASA OSIRIS-REx Touch And Go Sample Acquisition Mechanism (TAGSAM), though the JAXA Hayabusa mission demonstrated the capability preceding this moniker, meriting microgravity TRL 9 [121], [250]. The closest terrestrial example appears to be small single-use spring-loaded soil core samplers, though they are not automated; thus meriting terrestrial TRL 2 [251].

Skyhook / Harpoon is defined here as the use of a tethered system to collect and retrieve a sample of a body. This collection of methods is somewhere in-between penetrators and TAGSAM, as relatively large velocity differentials between the parent spacecraft and the sampling target are permitted, yet the sample has the potential to be returned to the parent spacecraft for analysis. This concept is best represented by the Khryselakatos concept by Zodiac Planetary Services, which uses a counterweighted set of tethers to collect a regolith sample from lunar orbit via a skyhook-like system [252]. A roughly spherical low lunar orbit is used, with a variable length tether approximately equal to the orbit height above the lunar surface on both ends. At the bottom of the arc when the tether is moving slowly relative to the lunar surface, a mechanism penetrates the lunar surface to collect a sample, then a subset of the mechanism is pulled back out when the slack in the tether runs out. Testing of the winch mechanism and penetrators has been reportedly conducted, thus meriting microgravity TRL 4 [253]. As for terrestrial applications, a number of studies have been conducted on using skyhooks at the edge of Earth's atmosphere to catapult air-launched vehicles into orbit [254], [255]. As the analysis has been quite preliminary and questions have been raised about material properties and stability characteristics, terrestrial TRL 2 is merited.

N/A: A null option is permissible here, since prospecting techniques exist that do not require sampling of the NEO. If a sufficiently accurate orbital remote sensing solution is fielded, direct composition analysis may be unnecessary.

B.2.2 Excavation

Excavation is the process of separating the ore from the NEO, or otherwise directly interacting with the NEO to release resources. Note that there are overlaps between the excavation and extraction options in some concepts, as authorities have devised ways to extract the resource from the ore without removing it from the NEO (e.g. 'optical mining') [89]. It is also important to note that assumptions about the consistency and toughness of the NEO bulk rock heavily influences the suitability of which excavation options to use, as seen in Table B-2 [80].

Table B-2: Excavation method compatibility with differing rock toughness [80]

Category	Approximate tensile strength	Exploration resolution	Terrestrial excavation technology	Available processing technology
0. ice composites	ice ~2 MPa to ? for composites	10 to 100 m	blasting, heating, distillation	phase separation in bags
1. friable rock	can be very low (~0.2 MPa) to 8 MPa	10 to 100 m	blasting, mechanical (ripping)	phase separation in bags, mechanical, chemical, magnetic
2. hard rock (crystalline)	8 to 33 MPa (Farmer, 1968)	10 to 20 m	blasting, mechanical (disc cutters)	mechanical, chemical, magnetic
3. metallic Ni-Fe (massive)	impervious to drill & blast	100 m	concurrent with processing	melting/smelting, carbonyl methods
3b. hard rock-metallic Ni-Fe	rock-metal boundary strength	1 to 100 m	various: rock-metal interface determines processing method	mechanical, chemical, magnetic; melting/smelting

There are two main aspects of excavation: handling of the regolith, and liberating the ore from the NEO. **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.

B.2.2.1 Containment

Clamshell Enclosure is an enclosed volume with a large hinged opening. Terrestrial examples of this include the Airbus Beluga XL with its top hinged door and the Boeing Dreamlifter with its hinged tail, meriting terrestrial TRL 9 [256], [257]. Note that these freighter aircraft use unpressurized cargo bays for structural regions, so modifications would be required to create a gas-tight enclosure if non-mechanical excavation means were selected. Such a concept for NEO is the Astrotecture et al. Robotic Asteroid Prospector with its clamshell 'containment vessel' [81]. Since this is a paper concept with no analogous systems fielded, microgravity TRL 2 is merited. Though not specified, gaskets with clamps are presumed to be used create a gas-tight seal.

Synched Bag refers to an enclosed volume with a constricting orifice that can be opened or closed to be gas-tight. The three main mechanisms for constricting orifices on earth appear to be drawstring bags (e.g. garbage bags), mechanical iris (e.g. camera shutter), and twisted diaphragms. Of these the twisted diaphragms appear to be the most gas-tight; the Kemutec Mucon series of iris diaphragm flow control valves are a COTS solution meriting terrestrial TRL 9 [258]. These devices work by using torsion to deform a flexible sidewall into a flattened hyperboloid disk to block the passage. The company website notes that these devices come with an internal diameter of up to 18 inches, are capable of holding pressures of 3 bar, and rated down to -75 °C (198 K).

When it comes to microgravity applications, the most thorough study of synched bag containment was conducted for the NASA Asteroid Retrieval Mission (ARM) [87], [259]. 'Risk reduction' of asteroid capture concepts culminated in a successful laboratory test of a one-fifth scale bag with inflatable supports[260]. This NASA prototype, along with the gas-tight plug with ratcheted tape sealing method under development by Flow Space, merits microgravity TRL 4 [261]. This containment option originated in the Keck 'Asteroid Retrieval Feasibility Study' at JPL, and has been adopted by several asteroid mining concepts including those by TransAstra and Deep Space Industries [18], [19], [89], [207].

Tube Sleeve is defined here as a cylindrical volume inserted into the subsurface that provides a gas-tight seal for additional processing. The core material inside this volume can be processed in place, or extracted from the borehole with minimum spillage. This technology is used on Earth to extract pristine ice core samples for gas composition analysis, meriting terrestrial TRL 9 [262]. HoneyBee Robotics has also successfully prototyped their Planetary Volatiles Extractor (PVEx), a perforated corer that forms a seal with the ground and heats the core while still in the borehole to extract volatiles [148]. The compacted seal with the ground and the high-fidelity laboratory testing conducted for the PVEx is felt worthy of microgravity TRL 5. Note that this perforated corer is considered here instead of the Mars 2020 rover sampling system, since the coring bit is not gas tight until placed back in its storage container [263].

Localized Membrane is defined here as the enclosure of an area with a perimeter surface seal and covering overhead to permit locally increased pressures. The closest analog on Earth appears to be a popup cleanroom tent coupled with inflatable air cushion berms [264], [265]. However these solutions either have an enclosed volume or a perimeter barrier seal but not both, only meriting terrestrial TRL 1. Colorado School of Mines is reportedly working on a concept study for a 'heated dome' Lunar ISRU concept with mirrors to focus sunlight, meriting microgravity TRL 4 [266].

B.2.2.2 Cut Rock

Auger Bit is defined here as a screw or drill with wide flutes that drills into material, then transports the material away from the cut. Drilling augers are commonly used to dig post holes and lay pipe in softer geologies on Earth. One such COTS design of note is the

Herrenknecht AG auger boring machine, meriting terrestrial TRL 9 [267]. The HoneyBee Robotics Mobile In-Situ Water Extractor (MISWE) extends this technology to NEO with experimental testing in a system to extract water from lunar regolith simulant under vacuum, meriting microgravity TRL 4 [88].

Corer is defined here as an elongated hollow cylinder, removing material from around a central cavity. Most designs have a smooth inner bore with an auger on the outside to carry kerf out of the hole, or use a drilling fluid for the same ends. Note that both corers that extract the core from the ground and process it in-situ are considered here. Corers are used to extract ice samples with both mechanical and thermal drill tips in use in Antarctica, meriting terrestrial TRL 9 [262]. For uses in space, HoneyBee Robotics has successfully tested mechanical corer prototypes that extract a core sample, with interchangeable bits and slots to cache samples, and visually inspect for core cohesion [191], [268]. This concept has been implemented and verified for use on the Mars 2020 rover, meriting microgravity TRL 7 [263]. HoneyBee Robotics has also successfully prototyped a perforated corer that heats the core to extract volatiles, and retracts without removing the core [148].

Percussive Drill is defined here as an elongated cylindrical cutting tool that rotates and provides a series of oscillating thrusts to create a circular hole. These impact drills specialize at penetrating high toughness geologic strata, and are available as COTS solutions, meriting terrestrial TRL 9 [269]. HoneyBee Robotics' 'The Regolith and Ice Drill for Exploration of New Terrains' (TRIDENT) extends this technology into outer space, and is self-reported as microgravity TRL 6 [148].

Optical Beam is defined here as the use of focused electromagnetic energy to remove material. This option is closely related to the 'spalling' extraction technique, especially when concentrated sunlight is used to cut into the ore. Elevated temperature cutting beams typically take the form of lasers or plasma jets on Earth, with higher power COTS plasma cutters meriting terrestrial TRL 9 [270]. For space applications, the most applicable technology is optical mining championed by TransAstra; experimental tests upon NEO simulants in a reasonably realistic laboratory environment merits microgravity TRL 5 [149].

Jet (plasma) is defined here as the use of a stream of matter to remove material. Note that by definition such a jet requires the injection of matter (e.g. water jet) or ambient gasses to interact with (e.g. plasma cutter) to work, requiring careful attention to mass flows and possible recovery of cutting fluids. Water jets and plasma cutters are both used on Earth, with higher power COTS plasma cutters meriting terrestrial TRL 9 [270].

Rotary Cutter is defined here as a cutting tool that rotates to produce straight line cuts. This rotating disc can have sharp protrusions (e.g. saw blade) or scoops on the end, with an axis of rotation parallel to the cut face. Disc cutters are available COTS with a variety of cutting heads and tooth designs on Earth, meriting terrestrial TRL 9 [271]. For space applications, much work has been done to develop designs for the excavation of lunar regolith, such as the NASA Regolith Advanced Surface Systems Operations Robot (RASSOR) [272]. The rotary scoop drum of the RASSOR is of particular interest here, as largely enclosed design of the drum could has been successfully tested for operation in lunar regolith simulant and would be far less susceptible to regolith dust dispersion than vibratory buckets like the NASA Vibratory Impacting Percussive Excavator for Regolith

(VIPER) [273]. It is thought the RASSOR could possibly be adapted for use in microgravity, if a pneumatic conveying system are added to empty the drum and scoop flaps were added to further prevent regolith from flying off. Since the RASSOR scoop itself is considered TRL 5 from prototype testing and HoneyBee Robotic's pneumatic conveyors are rated TRL 4, the unintegrated subsystem is felt to merit microgravity TRL 4 as the minimum of the two.

B.2.2.3 Powderize

Pneumatic Probes is defined here as injection of hot gasses into a shaft for the purpose of heating regolith, or fluidizing it for transport. This regolith can be fluidized into a granular solid for transport, or sufficiently heated for off-gassing of volatiles. The idea here came from David Kuck, with heated gas injected into a borehole within a NEO to sublimate volatiles out of the regolith [199], [274], [275]. This idea for fluidizing regolith has been used by the HoneyBee Robotics PlanetVac, a sample retrieval system that deploys a spring-loaded tube on the feet of a lander and vacuums up regolith and a cyclone separator that deposits a sample [276]. Further investigation by the company into non-penetrating suction heads and different sieves to capture the fluidized regolith merit microgravity TRL 5 [154]. A similar machine is available COTS on Earth from Herrenknecht AG called a reef boring machine, which applies suction behind a cutting head coupled with a cyclone separator and vacuum to capture ore, thus meriting terrestrial TRL 9 [277].

Borehole Heating is defined here as emplacement of a heating unit down a shaft for the purpose of heating regolith. This regolith can be fluidized into a granular solid for transport, or sufficiently heated for off-gassing of volatiles. In Antarctica, a similar concept is used to melt ice down in a borehole called a ‘rodwell’, thus meriting terrestrial TRL 9 [278]. This process was adapted for NEO by modeling by Wasilewski et al., hybridizing radiant heating in the borehole subliming comet ice, with buffer gas injection pressurizing liquid water to be pumped out [279]. A similar concept has also been used to drill ‘rodwells’ for Martian ISRU as part of the NASA RASC-AL Mars Ice Challenge, with automated heated drill prototypes meriting microgravity TRL 4 [280].

Rip/Fracture is defined here as breaking off chunks in a material along weak points through the use of rotating cutting heads. This includes the methods of horizontal direct drilling used for fracking operations, as well as tunnel boring machines (TBM) as small as 0.4 m diameter; a number of mature COTS solutions are available, meriting terrestrial TRL 9 [281], [282]. These machines typically fluidize the cut material in the form of a pumped aqueous slurry or injected pressurized air to transport it back out the hole they were cut in. TBM have also been considered for use on Mars and Luna to construct underground bases, with some preliminary analyses meriting microgravity TRL 2 [283]. Note that microgravity considerations are not typically taken into account here limiting applicability, though estimated excavation volumes and times can still be useful.

Cut Debris (kerf/spall) is defined here as fine powder or small chips resulting from cutting. Based upon the This technique is believed to be microgravity TRL 7, based upon test data from HoneyBee Robotic’s The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) subsystem in their Planetary Volatiles Extractor (PVEx) [147], [148]. Comparable mining industry activities on Earth are believe to permit terrestrial TRL 9.

Crush is defined here as the use of compressive forces to reduce particle size, exclusive of cutting. Twin rollers, hydraulic presses, and lever arms are included in this category. Mining industry activities using these items on Earth are believe to permit terrestrial TRL 9.

N/A: A null option is permissible here, since particle size reduction might be deemed unnecessary if sufficiently high temperatures are used during extraction. Note that increasing the surface area of the regolith through powderization can reduce the process time required, or increase the effectiveness of sizing and beneficiation techniques.

B.2.2.4 Sorting/Sizing

Filtration is the use of different phases of matter to differentiate between materials. Often a solid is separated out of a fluid, be it sediment from water or diesel exhaust particulate matter from air. These are COTS solutions for all sorts of filters on Earth, thus meriting terrestrial TRL 9. The OSIRIS-REx Touch And Go Sample Acquisition Mechanism (TAGSAM) uses a similar principle, with NEO regolith blown into a filter with nitrogen gas to collect a sample [101], [121]. As this mission is currently in progress, microgravity TRL 8 is merited.

Centrifugal (density) methods refer to the use of angular velocity to induce artificial gravity within an inertial reference frame. These methods are relatively mature on earth with TRL 9, ranging from Dyson vacuum cleaners to nuclear enrichment centrifuges. NASA has looked at 'cyclone dust separation' and considered this to be microgravity TRL 4 in 2015, noting that these systems are voluminous and require filters to be manually replaced at regular intervals [152].

Sieves describe the use of mechanical perturbation to differentiate between materials. The most common is a sequence of grates or mesh with different sized holes, which are used to sort granular solids like gravel by size and thus merit terrestrial TRL 9. These are termed passive/'dumb' sieve systems. Also considered in this category are 'smart' automated vision systems with mechanical effectors, like those used for quality control in the food industry. NASA has looked at 'non-clogging and/or self-cleaning sieves' to sort regolith with 'smart' cleaning effectors, and prototypes have has been successfully tested in reduced lunar gravity aircraft then vacuum, meriting TRL 4 for microgravity [152]. Note that HoneyBee Robotics has also looked into sieves for microgravity applications using pressure differentials to drive flow, though their solutions are neither self-cleaning nor automated [154].

N/A: A null option is permissible here, since a regolith of sufficiently homogenous or volatile rich composition may not require upgrading to be a viable ore. Alternatively, excavating a sufficient quantity of overburden may be sufficient, with diminishing returns not justifying further efforts to improve the grade of ore.

B.2.3 Extraction

Extraction refers to the removal and purification of resources of interest from their ores. Note that several of the benchmark concepts examined intermingle functions from the extraction and excavation steps, to drastically reduce the volume of material to be excavated. Thus, it should be noted that these extraction steps do not necessarily occur outside the NEO, with varied options to reflect this. **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. Note that purification of volatiles counts here as well as upgrading ore, though mechanical means of separation like sizing fall under the excavation system instead. Lastly, **Volatile Capture** describes methods to isolate the resource(s) extracted from the ore, for further refinement or storage.

B.2.3.1 Heating [Primary]

Focused Sunlight heating is defined here as the concentration of ambient light by focusing it for the purpose of increasing the thermal energy of a material. On Earth, utility scale solar thermal power plants use concentrated sunlight to heat a working fluid for an associated thermal gradient system, with multiple designs in use today meriting terrestrial TRL 9 [284]. TransAstra is spearheading development of this technology for NEO, partnering with the Colorado School of Mines to experimentally test the behavior of NEO simulants when exposed to a focused spotlight in a vacuum chamber [149]. Four different NEO simulants with two levels of cohesion have been reported as tested to date, with $600\ \mathrm{W/m^2}$ beam measured for a 3 cm diameter focus. These reasonably realistic laboratory test conditions and preliminary presented results are felt to merit microgravity TRL 5. Note that this technology was recently selected to be developed and integrated for ground test under a NIAC Phase III contract, with a miniaturized prototype system termed 'Mini Bee™' developed de-risk this optical mining technique to TRL 6 [66], [96], [165].

Light (lamp/laser) heating is defined here as using coherent wavelengths of artificial illumination, focusing it for the purpose of increasing the thermal energy of a material. On Earth, lasers have been used to bend metal parts by mild diffusion of laser cutter beams in a process called laser induced thermal forming, or laser forming [285]. However the large heat affected zones and longer takt times characteristic of the process have limited its use to prototypes for niche applications, meriting terrestrial TRL 8 due to the lack of COTS solutions. For space applications, Laser Induced Breakdown Spectroscopy (LIBS) has been proposed as a sampling mechanism for interplanetary rovers, that works by vaporizing rock with a laser. Studies showing possible compact LIBS system designs have been published, along with test data from similar systems have been published in the literature, though for lower power lasers (e.g. 0.2 W) [286], [287]. Also worthy of note is research on planetary protection using laser ablation to generate thrust, with published tests of a 150 W laser beam on basalt [288]. Together, these research efforts merit microgravity TRL 4.

Resistance (electrical) is defined here as current flow for the purpose of increasing the thermal energy of a geologic material. Thermal corer drills are used to melt layers of icepack in order to extract ice core samples, thus meriting terrestrial TRL 9 [262]. In space, the HoneyBee Robotics Planetary Volatiles Extractor (PVEx) proposes to utilize an electric heater within the wall of a corer to warm the core sample and extract its volatiles though a nested perforated sleeve. HoneyBee Robotics reports TRL 5 for this concept [148]. Note that TransAstra has also tested this method by heating Orgueil asteroid simulant in a vacuum chamber, later noting that this ‘bake in a bag’ approach produced relatively low yields of volatiles in their cold trap [165], [204].

Dielectric (microwave) or high-frequency heating is defined here as the use of electromagnetic waves that penetrate an object to increase its thermal energy via radiative heating. Note that this includes concentrated masers and more diffuse beams such as in a microwave oven. In industry, microwave volume heating is used to tasks such as pasteurize milk, with COTS solutions available meriting terrestrial TRL 9 [289]. It is also worthy to note that the U.S. military has also developed moderately focused millimeter wave heating systems for crowd control [290]. For space applications, NASA JPL has reportedly completed a breadboard test of microwave heating of lunar regolith simulant to extract water, meriting microgravity TRL 4 [266], [291].

Jet (Heated) is defined here as using a stream of hot matter to increase the temperature of the target body. This option includes plasma cutters as well as steam pressure. Note that mass is inherently expended the jet or stream, though the introduction of increased pressure in a sealed chamber makes heating by convection a possibility. On Earth, COTS plasma cutters are readily available, meriting terrestrial TRL 9 [270]. Modern plasma jet solutions rapidly cut through metal, with lower cost shop-air plasma and precision inert gas models available. In space, much research has been done on using varying types of plasma jets for electric propulsion, with many flight articles of designs such as hall thrusters and gridded ion engines to date [292]. However, these designs tend to produce relatively diffuse plasma density profiles and are far lower power than would be required to heat rock. Thus these more mature concepts are not considered here. An idea for a plasma torch paired with a laser was proposed to melt NEO regolith, though little analysis was done on this mechanism thus meriting microgravity TRL 1 [197]. The study's authors do concede that the storage mass and volume available for the plasma jet consumables would be very limited, limiting its useful life.

Induction heating is defined as the use of a rapidly oscillating magnetic field to induce eddy currents which warm the material through electrical resistance. Inductive heating is a high powered electrically powered heating process for metals that rapidly heats from the inside out, and is found in high end cooktops for home use [293]. For industrial applications, induction furnaces with heating power from kW to MW are available COTS and commonly used to melt ferrous metals and precious metals [294]. For space applications, induction heating has been viewed as a method to induce vacuum thermal decomposition via pyrolysis in regolith, with a focus on oxygen production from lunar regolith [295]. Experiments from Dominguez's dissertation on lunar regolith, as well as the use of induction furnaces to melt carbonaceous chondrite meteorites on Earth, are together felt to merit microgravity TRL 4 [295], [296].

B.2.3.2 Beneficiation

Centrifugal (density) methods refer to the use of angular velocity to induce artificial gravity within an inertial reference frame. These methods are relatively mature on earth with TRL 9, ranging from Dyson vacuum cleaners to nuclear enrichment centrifuges. NASA has looked at 'cyclone dust separation' and considered this to be TRL 4 in 2015, noting that these systems are voluminous and require filters to be manually replaced at regular intervals [152]. However, the ISS Carbon Dioxide Removal Assembly (CDRA) includes a centrifugal pump as a phase separator between methane and water [297], [298]. This recent upgrade to the ISS CDRA is felt to merit microgravity TRL 9.

Magnetic Separation is the use differences in charge polarization (or lack thereof) to sort materials. Note that magnetic fields cannot do work, so only changes in curvature to the paths particles already in motion are possible. These techniques are commonly used for 'magnetic finishing' of iron ores, and therefore merits terrestrial TRL 9 [299]. NASA has looked at ‘magnetic beneficiation’ for dust separation, but it failed in lab testing thus receiving TRL 1 for microgravity [152].

Electrostatic Separation is the use of differences in charge (or lack thereof) to sort materials. ‘Drum electrostatic separators’ have been tested in pilot plants by the phosphate mining industry meriting terrestrial TRL 7, but the integrated systems proved overcomplicated for production and research is ongoing for better alternatives [300]. NASA has looked at ‘electrostatic beneficiation’ to sort lunar regolith, and prototypes have has been successfully tested on reduced gravity aircraft, meriting TRL 4 for microgravity [152].

Molten Powderization is the process of converting heated liquid metal into a granular solid. This is commonly used in the powdered metals industry to produce granular solid feedstocks for casting and 3D-printing, meriting a terrestrial TRL of 9. NASA has looked at ‘molten-to-powder metal technologies’ to atomize molten metal into spherical granular solids for additive manufacturing, and gave TRL 5 for microgravity [152]. Note that this technology is incompatible with volatiles due to temperature, and would be a means of repurposing tailings from a refining process (such as solid oxide electrolysis to extract oxygen from metal oxides).

Reforming is defined here as the injection of chemical agents to react with the ore. Note that many of the processes described in § B.2.4.3 Crack Hydrocarbons (e.g. steam reforming) apply here, as well as any other chemical additives. Collectors, defoamers, float oils, frothers, flocculants, slurry pumping aids, depressants, dewatering aids, and pH modifiers are all classes of chemicals used for this in the mining industry on Earth, meriting a terrestrial TRL 9 [301]. Since the injection of non-catalyst chemical agents implies a initial mass penalty from added consumables, ISRU SoS designs tend to avoid using them unless the chemicals can be recovered and the recycling systems involved are worth the added complexity. One such system proposed for microgravity applications is the Lunar Organic Waste Reformer, which includes the injection of steam and oxygen in a reformer unit [302]. This concept was developed into a lab scale prototype called the Carbonaceous Asteroid Volatile Recovery system (CAVoR) and tested on unrecovered petroleum simulants, meriting microgravity TRL 5 [38].

Leachate (Chemical) is defined here as the injection of fluids into a material for the purpose of chemical changes to the material to aid the removal of substances of interest. Please note that biological processing methods to these ends are specifically excluded in this analysis due to planetary protection concerns. Entire classes of chemicals exist for use in the mining industry, including collectors, defoamers, float oils, frothers, flocculants, slurry pumping aids, depressants, dewatering aids, and pH modifiers [301]. On Earth, this technique is considered to be solution mining, or in-situ mining, and is used to extract resources like copper and uranium [303]. Documentation of commercial solution mining of copper by injecting acidic aqueous solutions, merits terrestrial TRL 9 [304]. For space applications, leachates have been noted as a possible source of contamination for supplies in storage (e.g. drinking water) as well as a possible resource extraction technique [305], [306]. NASA has looked at 'acidic ionic liquids for dissolution of regolith for electrolytic oxygen production or igneous asteroids for pure metals production' and considered this to be microgravity TRL 2 in 2015 [152]. Their main concerns included recycling of the reagents and a long operational life without maintenance.

N/A: A null option is permissible here, since concentrating the ore may be unnecessary for smaller scale operations with a long permissible operational time constraint. In addition, this option is especially relevant for designs with comingled excavation and extraction operations that include NEO resource processing preformed inside the NEO itself, as the ore must be physically extracted to use non-thermal methods of concentrating the orebody.

B.2.3.3 Volatile Capture

Cold Trap (Deposition) methods involve cooling to induce sublimation of gasses. This use of phase changes is known to separate materials by means of differing phase transition properties (esp. boiling point at pressure), at low operating pressures conducive of direct transition from gasses to solids. Cold traps are available COTS, and primarily used to protect vacuum pumps as they remove vapors [307]. These cold traps tend to come at three recommended temperature levels: -50 °C (223 K) for water, -85 °C (188 K) for nonpolar solvents, and -105 °C (168 K) for alcohols. In addition, Japanese researchers studied water ice crystal growth with different dissolved impurities on the ISS in 2008 and 2014 [308]. HoneyBee robotics has also successfully tested a prototype aluminum cold trap for their Planetary Volatiles Extractor (PVEx), together meriting microgravity TRL 5 [148].

Condenser methods involve cooling to induce solidification of liquids. These methods typically require higher operating pressures than cold traps, in order to be above the triple point on the material's phase diagram and have a liquid phase be feasible. On Earth pressure is not a problem, with COTS industrial dehumidifier solutions for humid air readily available, meriting terrestrial TRL 9 [309]. Multiple modules on the ISS have condensing heat exchangers (CHX) incorporated to reduce humidity [310]. In addition, recent crew capsules under development also incorporate humidity control technologies, indicating that knowledge has been conserved over the years and microgravity TRL 9 is merited [311].

Sorbents refer to methods where materials bond to or otherwise absorb a chemical and can later be made to reversibly release the same chemical. Materials that absorb water are typically referred to as desiccants, with carbon dioxide scrubbers preforming an equivalent function. Sorbents are used for a number of applications on Earth, with a particularly novel automated COTS solution being the Zero Mass Water SOURCE Hydropanels, meriting terrestrial TRL 9 [312]. These systems use a staged pair of desiccant drums to extract moisture from the air with relative humidity as low as 5%, and store it as potable water using only sunlight [313]. In space, desiccants have been used to regulate humidity for experiments on the ISS, though published solutions are not currently automated [314]. The ISS Carbon Dioxide Removal Assembly (CDRA) is automated scrubber system, though it was sent to vent the carbon dioxide to space for the recharge cycle [139]. Note that a Sabatier reactor has since been added to improve oxygen recovery a decade later, with methane now vented instead [138]. A number of improvements have been proposed and additional systems under development for future manned capsules, leading to an impression of retained design knowledge meriting microgravity TRL 9 [315], [316].

Vacuum Distillation refers to lowering the ambient pressure in a vessel to encourage evaporation of chemical species by suppressing their boiling point. This technique is used in oil refinery distillation towers on Earth to separate crude oil into hydrocarbons of differing molecular weights, thus meriting terrestrial TRL 9 [317]. HoneyBee Robotics has tested vacuum distillation upon frozen NEO regolith simulant, and reports microgravity TRL 4 [318].

B.2.4 Refining

Refining is defined here as the processing of the resource from an intermediate state into a readily useable form termed a consumable. The extent of capabilities required within the refining group depends heavily on which propellant is selected to be produced by the SoS NEO ISPP. In particular, steam monopropellant does not require further processing if the rocket engine is reasonably tolerant of impurities. Thus all categories associated with the refining group have a null option, except for quality control of the process. Since the selected mission focuses on producing propellant, metal processing and fabrication methods are not considered. Furthermore, biological processing methods were specifically excluded due to the risk of violating planetary protection protocols in the case of a serious accident or crash landing.

Make Oxygen refers to methods to obtain elemental oxygen from NEO resources. Note that splitting water is the most commonly considered way to produce oxygen, but other methods are considered for earlier testbed missions involving partial ISPP (bring fuel, make oxidizer on site). **Make Hydrogen** refers to methods to obtain hydrogen gas; since methane production is being considered, chiefly ways to disassociate water will be considered, with each method referring to a different way to input the energy required for the reaction. **Crack Hydrocarbons** refers to methods to refers to methods to decompose organic molecules, especially by reducing the length of hydrocarbon chains. Normally this is required to procure carbon from the NEO to produce methane, but it also may have the benefit of boosting water extraction as well. **Make Methane** or methanation, refers to methods to build simple hydrocarbons from other chemical species. Note that methane is arguably the simplest hydrocarbon, and that this category is only required for methalox propellant. **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. If the propellant is not to spec, it is recursively reprocessed until it is. Note that a variety of intermediate steps are implied by the combinations of options selected though not explicitly included here. One such example is the use of a centrifugal pump to separate gases from liquids as well as pressurize the flow for the next stage, like in the ISS CDRA [297], [298].

B.2.4.1 Make Oxygen

Carbothermal Reduction is defined here as the addition of carbon or hydrogen containing compounds to react with metal oxides and remove their oxygen. Secondary processing is normally required to extract the oxygen from the by-products. This process is commonly used to reduce iron ores with coke in a blast furnace on Earth, meriting terrestrial TRL 9 [319]. Efforts to adopt these methods for lunar ISRU have also been made, with a thorough analysis by NASA COMPASS meriting microgravity TRL 3 [320].

Split Water refers to methods to disassociate water into elemental hydrogen and oxygen, agnostic about the method used to do so. Thus, Proton Exchange Membrane (PEM) electrolyzers will be assumed to be representative of this option, as they have flight heritage. COTS solutions are available, metring terrestrial TRL 9 [321]. PEM electrolysis is also used on the ISS to generate crew oxygen, meriting microgravity TRL 9 as well [150].

Metal Electrolysis is defined here as the dissociation of metal oxides to produce elemental oxygen. Boston Electrometallurgical Corporation has demonstrated the production of iron ingots from molten iron ore, meriting terrestrial TRL 6 [322]. This company was actually spun off a successful earlier effort to electrolyze molten lunar regolith simulant, meriting microgravity TRL 5 [323], [324].

Ionic Liquid Reduction is defined here as the addition of carbon or hydrogen containing compounds to react with metal oxides and remove their oxygen. Researchers from NASA Goddard report that microgravity TRL 2 has been achieved [266].

N/A: A null option (N/A) is permissible here, since making oxygen is unnecessary if a propellant without an oxidizer is used, such as steam monopropellant. Producing hydrolox and methalox both require oxygen production, as do longer missions with astronauts. Since robotic missions without an oxidizer are considered, this is a valid option.

B.2.4.2 Make Hydrogen

Acidic Electrolysis (Voltage) is defined here as the splitting of water by electric charge potential, where excess hydrogen ions are the charge carrier ($pH < 7$, excess H^+) for the half-cell reactions separated by a liquid electrolyte. Proton Exchange Membrane (PEM) electrolyzers are currently the market leader in this category, with watt to megawatt scale COTS solutions available, meriting terrestrial TRL 9 [321]. PEM electrolysis system is also a key subsystem within the ISS Oxygen Generation System (ISS OGS) on the U.S. side, meriting microgravity TRL 9 as well [150].

Alkaline Electrolysis (Voltage) is defined here as the splitting of water by electric charge potential, where excess hydroxide ions are the charge carrier ($pH > 7$, excess OH^-) for the half-cell reactions separated by a liquid electrolyte. Alkaline electrolysis with liquid electrolytes is a mature technology, scaling from watt to gigawatt COTS solutions available, meriting terrestrial TRL 9 [325]. Alkaline electrolysis systems tend to be more electrically efficient than PEM electrolysis systems, but they also tend to be more voluminous and heavy. Some alkaline electrolysis experiments have been performed in microgravity environments, but no known systems developed, thus meriting microgravity TRL 3 [326].

Solid Oxide Electrolysis (Voltage/Heat) is defined here as the splitting of water and/or carbon dioxide using electric charge potential and thermal energy, where negatively charged ions are used for the half-cell reactions separated by a solid electrolyte. The major advantage of Solid Oxide Electrolysis (SOE) technology is its flexibility, tolerating more impurities, co-electrolyzing carbon dioxide and water, and using both heat and voltage to split molecules thus improving efficiency. On earth pilot plants that use SOE to split water as a precursor step in ammonia production are under development, thus meriting terrestrial TRL 6 [327]. In space, the Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 rover has had its SOE undergo verification, but this is designed for use in a gravity well. Thus the unintegrated microgravity TRL 5 is merited [328].

Thermolysis (Heat) is chemical decomposition through achieving a sufficiently high temperature in the presence of a catalyst [329]. On Earth a number of applications have been envisioned and experiments conducted for thermolysis of water, but no tested cycle has yet meet analytical performance goals, thus meriting TRL 2 [330]. The use of thermolysis has also been proposed to split carbon dioxide during Martian aerocapture, and to split lunar water as well [331], [332]. Still, these studies only report basic desired principles for the thermolysis subsystem, meriting microgravity TRL 1.

Photocatalytic (Light) splitting or 'artificial photosynthesis' is defined here as the chemical decomposition of water through exposure to sunlight in the presence of a catalyst. Great strides have been made in this field lately, with a prototype panel to split water validated in a laboratory environment, meriting terrestrial TRL 4 [333]. Artificial synthesis has been touched upon as an option to split Martian carbon dioxide with little analysis behind it, thus meriting microgravity TRL 1 [334].

N/A: A null option (**N/A**) is permissible here, since splitting water is unnecessary if steam monopropellant is used. Producing hydrolox requires water to be split, while producing methalox usually requires additional hydrogen gas unless produced by cracking more complex hydrocarbons and discarding the excess and other elements produced.

B.2.4.3 Crack Hydrocarbons

Reverse Water Gas Shift reaction is defined as reacting carbon dioxide or hydrogen together to produce water, according to equation (4). Comparatively little energy is required to drive the endothermic reaction, though very high concentrations of reactants are required and the reaction occurs slowly unless high temperatures are used.

$$CO_2 + H_2 \Rightarrow CO + H_2O \tag{4}$$

Steam Reforming is defined here as the injection of heated water to decompose hydrocarbons into shorter chain hydrocarbons, or carbon monoxide and hydrogen. Steam methane reforming is the opposite reaction to equation (5).

Pyrolysis (Heat) is defined here as the thermal decomposition of hydrocarbons. Based upon optical mining testbed experiments by TransAstra and their research partners like in Figure 5-10, microgravity TRL 9 is felt to be merited [50], [149], [204]

Thermal Oxidation (Burn) means the use of combustion at elevated temperatures to decompose complex organic molecules into simpler molecules such as carbon dioxide and water. Note that these systems consume a significant supply of oxygen gas during their operation, but are extremely versatile in the chemical species they can handle. A variety of COTS solutions for various designs of thermal oxidizers are available on Earth, meriting terrestrial TRL 9 [335]. The ISS Catalytic Oxidizer Assembly (COA) is part of the Trace Contaminant Control System, operating at 400 °C using a palladium pellet bed [336]. Since comparable systems have not been developed recently for microgravity applications, microgravity TRL 8 is merited.

Fluid Catalytic cracking of hydrocarbons through the use of an intermixed catalyst. This could include the Bosch reaction, which reduces carbon dioxide with hydrogen into elemental carbon and water. Oil refinery fluid catalytic crackers are believed to be terrestrial TRL 9.

N/A: A null option is permissible here, since cracking hydrocarbons is unnecessary if steam monopropellant is used and produced from ice or hydrated minerals. Cracking hydrocarbons can be used to increase the yield of water from the NEO, though processing becomes more complex. For the three propellant options considered, this category is only required for methalox propellants.

B.2.4.4 Make Methane

Fischer-Tropsch Process, also known as the reverse methane steam reforming reaction when used to make methane, is the process of reacting carbon monoxide with elemental hydrogen to produce methane and water, according to equation (5).

$$\mathrm{CO} + 3\ \mathrm{H_2} \Rightarrow \mathrm{CH_4} + \mathrm{H_2O} \tag{5}$$

Sabatier Process is reaction of carbon dioxide with hydrogen to produce methane and water, according to equation (6). The ISS Carbon Dioxide Removal Assembly (CDRA) has a Sabatier reactor installed to help process the captured carbon dioxide back into oxygen, with its successful operation meriting microgravity TRL 9 [138].

$$\mathrm{CO_2} + 4\ \mathrm{H_2} \Rightarrow \mathrm{CH_4} + 2\ \mathrm{H_2O} \tag{6}$$

Photocatalytic methanation is the production of methane using electromagnetic radiation to advance the reaction. One such process has been proposed utilizing sunlight and copper platinum nano-catalysts to process carbon dioxide and water vapor into methane, though a series of intermediary reactions summarized in the overall reaction in equation (7) [337]. Their component test merits terrestrial TRL 3. The use of photocatalytic methanation has also been proposed for ISRU applications without further analysis, meriting microgravity TRL 1 [334].

$$\mathrm{CO_2} + 2\ \mathrm{H_2O} + 8\ h\nu \Rightarrow \mathrm{CH_4} + 2\ \mathrm{O_2} \tag{7}$$

N/A: A null option is permissible here, since making methane is unnecessary if steam monopropellant or hydrolox is selected as the propellant. Here, making methane refers to building up carbonaceous compounds from the hydrocarbon feedstocks that were broken down into simpler molecules by cracking. For the three propellant options considered, this category is used for methalox propellants.

B.2.4.5 Quality Control

Process Monitoring refers to the use of sensors integrated into the processing equipment to automatically check if the state of the system is acceptable. If all data points are nominal, it is implicitly assumed that the propellant output meets the specification. For example, this can take the form of a digital twin emulating the system state to compare against prior outcomes, or seeing if process control limits are exceeded.

Output Check is defined here as periodic sampling of the produced propellant output to ensure that it meets the specification. This act of sampling typically consumes a small amount of propellant, and is best suited for continuous flow processes.

Batch Quarantine is defined here as the holding of a specific quantity of propellant after it has been produced and ensuring it meets the specification, before putting it into storage. This checking of the propellant characteristics can be done in-situ, or consume a small amount of propellant. This method is best for batch processes, or when strict adherence to quality standards is paramount.

B.2.5 Storage

Storage refers to methods for preservation of consumables for future use. Note that durations may be on the order of months depending upon the time on station. This includes a container to hold the consumable, as well as techniques to minimize losses over time (e.g. boil off). **Medium** refers to the form of matter that the consumable is in during storage; each form tends to have a closely related confinement method, on which the TRL assessment is based. **Insulation** refers to passive methods to maintain the consumable within a preferred temperature range for storage. Note that multiple insulation methods are typically used together, though they are discussed individually here.

<u>B.2.5.1 Medium</u>

Cryogenic Liquid storage is defined as the storage of standard temperature and pressure gasses at or below the point which they become liquid, typically below temperatures of 150 °C (123 K) [338]. Liquid nitrogen is commonly used to cool industrial processes and lab equipment on earth, as well as cryogenic liquid propellants for orbital launch vehicles like the SpaceX Falcon 9 [339], [340]. However, these are generally short term storage options on the order of hours requiring periodic refills to top off their stores. Longer term solutions utilizing solely input electricity to keep materials cool for months are also available, such as the COTS Mirai Cryo series of refrigeration machines, thus meriting terrestrial TRL 9 [341].

For space applications, cryogenic propellant storage and transfer is a very active area of research, with over a dozen funded efforts within NASA [342]. Cryogenic liquid storage dates back to the Apollo Program, with hydrogen and oxygen stored in dewars within the

Apollo Service Module, though interest has waxed and waned over the years [343], [344]. Flight proven technology exists to store cryogenic liquids, though boil-off losses are generally felt to restrict possible missions. Acceptable boil-off losses for existing second stage orbital rockets via venting are generally considered on the order of hours, advanced insulation and re-use of boiled off gasses extends this to days, with large-scale cryocoolers having the potential to extend this storage time to months.

Basic research on microgravity fluids management is still being performed, such as the NASA Zero-Boil-Off Tank (ZBOT) series of experiments being conducted on the ISS to study how fluids heat, gas pressurizes, and jets mix in microgravity [342], [345]. An integrated cryocooler is included to reset the experiment, along with several heating elements. At the vehicle level, the ground test prototype of the NASA SLS Exploration Upper Stage called the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) appears to be the first effort to scale up cryogenic storage for use for propellants [346]. This system does not appear to have an attached cryocooler, instead attempting to use boiled-off gasses for evaporative cooling. Testing of SHIIVER has reportedly been completed, thus meriting microgravity TRL 6 due to the much larger size and decades since past in-space cryogenic hydrolox storage efforts [342].

Cryogenic Solid storage is defined here as the storage of rocket engine propellants in solidified form at extremely low temperature. Solid rocket motors are excluded from this analysis, with the properties of water ice and methane being of particular interest. On Earth, ice is generally used closer to its freezing point, and the extremely low temperatures required for solidification of ordinary gases like oxygen and methane restrict their applications. Thus, most applications are limited to basic research on sublimation rates and superconductivity, meriting terrestrial TRL 2 [347], [348]. However, cryogenic solids were able to find applications in space vehicles in the 1960's and 1970's. Solid oxygen and nitrogen were investigated as a way to generate breathable air for astronauts for compact life support systems for long duration missions [349]. In addition, solid methane and ammonia blocks were sublimated as passive cryogenic coolers for instruments; the cryocooler flown on Nimbus 6 in 1975 is of particular interest [350], [351]. However, this cryocooler technology was abandoned over the years in favor electrically operated cryocoolers with longer life, with the long lapse in interest demoting this technology to microgravity TRL 4. Still, some interest in solid storage has reappeared of late, with a cabin air dehumidification by ice deposition being ground tested recently [352].

Pressurized Gas is defined here as the storage of chemicals at high pressure in gas phase. State of the art technologies include Composite Overwrapped Pressure Vessels (COPV) for low mass tanks, and stainless steel for low cost corrosion resistance [353]. These systems are very mature, with design standards codified for different materials within ANSI/AIAA standards, ASME codes, and European Commission directives [354]–[356]. Thus, it is felt that both terrestrial and microgravity TRL 9 is merited. It is important to note that when pressurized gas containment vessels are put on spacecraft they are typically used as secondary systems, like tank pressurization and low thrust reaction control systems, not primary propulsion. This is largely due to cold gas thrusters tend to have very low specific impulse ($I_{sp}{\sim}60$ s for Nitrogen), and tend to be incompatible with liquid rocket engines due to drastically lower cooling capacities [357]. In addition, pressurized gasses tend to require thicker walls than cryogenic liquids tanks of the same size due to higher hoop stress, not to mention that gasses are less dense than liquids. However spacecraft operating only within the vacuum of space are not volume constrained after launch, with deployable structures and/or tankage manufactured in-situ offer interesting prospects for future use.

Granular Solids is defined here as a storage in a multiphase emulsion or small chunks that can flow. This category can also include pelletized solid propellants and mass driver ammunition, but the focus here is on slurries where a solid is suspended in a liquid. Coolant slurries such as 'pumpable ice' fall into this category, where water ice chunks are put in a mildly saline aqueous solution to flow better. COTS solutions such as Sunwell's DeepChill merit terrestrial TRL 9 [358]. For space applications, slush propellants made by storing a material at its triple point (solid, liquid, and gas coexist) offer the possibility of densified low-slosh propellants without additives [359]. A number of system benefit studies have been performed using conceptual designs for slush hydrogen and slush methane, with a recent resurgence in interest for new European launch vehicles [360]. Still experimental characterization is lacking with many more concepts for mechanisms than test data, with little experimental work done since the X-30 National Aerospace Plane was cancelled in the early 1990's [361]. Thus, it is felt that microgravity TRL 3 is merited.

Chemical storage is defined here as reversibly binding one material to another using strong or weak molecular bonds. Most development in this area has been around hydrogen storage, in order to reduce the volume required at the cost of additional container mass. Small vehicles have been retrofitted as testbeds for metal hydride storage of hydrogen on Earth, meriting terrestrial TRL 6 [362]. Some sources say that the Cassini–Huygens mission carried small metal hydride canisters, though these claims were not independently verified [363]. More recently, in-situ production of nano-porous silicon has been proposed to create solid state hydrogen storage on site, with detail on the processing technique meriting microgravity TRL 2 [364].

Gel storage is defined here as the use of additives to make the stored fluids more viscous, or otherwise have non-Newtonian properties. Shear thinning properties are normally exhibited, in order to reduce sloshing and spill hazards while stored, yet also be pumped easily and aerosolize properly upon injection [365]. Pseudo-plastics and Bingham plastics are widely used in industrial applications such as drilling fluid and food products like mayonnaise, thus meriting terrestrial TRL 9 [366]. Space applications have been harder to come by, chiefly being the development of gel propellants. Research has been conducted to verify rheological models and laboratory investigation of good compositions with rheological testing and controlled burns is currently underway, thus meriting microgravity TRL 4 [365], [367]. Of particular interest is research into gelled hydrogen and hydrogen-methane blends.

B.2.5.2 Insulation

Multi-Layer Insulation (External) or MLI is defined here as the use of a stack of many sheets of material with differing properties in order to drastically reduce heat transfer. Layers typically alternate between metalized reflectors and mesh spacers, knitted together by threads and/or thermal tape, with covers on exposed ends [368]. MLI was developed for and commonly used on satellites to tailor thermal properties, with many COTS options available thus meriting microgravity TRL 9 [369]. Cryogenic systems on Earth also use similar multilayer ‘superinsulation’, with advanced honeycomb metalized attic insulation by yellowblue falling into this category as well, thus meriting terrestrial TRL 9 [370], [371].

Coatings (External) is defined here as adding a thin layer of material to tailor the properties of a surface. Note that MLI includes customizable coatings at the topmost layer [369]. A number of other specialized coatings to control the ratio of absorptivity to infrared emissivity such as polished metals and grayscale paints [166]. Of particular note is the white ceramic coating used on the sun facing heat shield of the NASA Parker Solar Probe, thus meriting microgravity TRL 9 [372]. Also worthy of note is a specialized ultra-white thermal control coating under development at NASA Kennedy that claims to have ultra-low absorptivity ($\alpha \approx 0.00048$) to passively achieve a 50 K surface temperature [373]. A variety of thermal spay coatings conforming to ISO, AMS, and FDA regulations are also available for use in industrial applications on Earth, especially for metallic parts, thus meriting terrestrial TRL 9 [374].

Sun Shade / Sunshield or sun heat shield is defined here as a secondary structure that occludes and/or reflects solar radiation away from an object. Many types of shading devices exist on Earth, such as pavilions, parasols, and fabric tarps. Of particular interest is poly-aluminium knit fabric such as Green-Tek Aluminet which is primarily used in agriculture as a mesh liner to reflect infrared light while permitting the passage of diffuse visible light; this technology merits terrestrial TRL 9 [375]. For space applications, shading sunlight is most commonly used as sun 'heat shields' as part of thermal protections systems for spacecraft operating close to the sun. The most recent example is the NASA Parker Solar Probe (formerly Solar Probe Plus), with carbon composite foam sandwich with a reflective ceramic coating, with several successful perihelion transits to date [376]–[378].

Low temperature shading applications are also fairly advanced, with the NASA/ESA/CSA James Webb Space Telescope's sunshield is on the cusp of microgravity TRL 8 after many verification tests [379]. Note that this five sunshield is expected to have a temperature of 85 °C (358 K) on one side and 50 K on the other, which provides an attractive proposition for cryogenic propellant storage. One such concept is the United Launch Alliance's on-orbit refuelling node upgrade to their Advanced Cryogenic Evolved Stage (ACES) [61]. Since the James Webb's sunshade operates at lower temperatures, it has been selected as the type example over the Parker Solar Probe.

Body Lining (Internal) is defined here as material added to the inner wall of a tank that reduces heat transfer. These coatings may be applied for another purpose like reducing corrosion of metal and/or gas leakage through a wall but also provide interfacial thermal resistance. On Earth, elastomeric coatings and epoxies are used at cryogenic temperature equipment, with COTS examples meriting terrestrial TRL 9 [380], [381]. Coatings for high temperature applications are also available, termed thermal barrier coatings and usually comprised of ceramic materials. In space applications, liners appear to primarily be used to prevent leakage or corrosion, not for thermal management purposes. Large propellant tanks appear to be made out of aluminium or titanium alloys, or coated with electroplated pure aluminium after the fact [382]. Small propellant tanks appear housed in Composite Overwrapped Pressure Vessels (COPV), which often have a metal or plastic lining to prevent gas leakage [383], [384]. Although these capabilities are generally not implemented for thermal management purposes, they are widely used in the industry and thus microgravity TRL 9 is merited.

Dewar / Vacuum Shell is defined here as the use of an internally confined cavity between layers largely absent of matter for the purpose of reducing heat transfer. On Earth, COTS solutions exist for small vacuum flasks to cryogenic bulk storage of a million liters and even vacuum insulated pipes, thus meriting terrestrial TRL 9 [385]. In space, the use of dewars dates back to the Apollo Program, with hydrogen and oxygen stored in dewars within the Apollo Service Module, to power the fuel cells and for astronaut breathing air [343], [344]. A similar setup was also used aboard the NASA Space Shuttle's Power Reactant Storage Assemblies (PRSA). The use of dewars continues today, especially within systems for imaging equipment, thus meriting microgravity TRL 9 [386].

B.2.6 Material Handling

Material Handling examines methods for how to transport masses between locations [140]. The primary considerations herein are the state of matter, and how energy will be input to do work upon the system. Two primary matter flows are considered in this work: granular solids, and fluids. **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 [152]. In addition, **Work Input** into the system refers to the primary method that energy is supplied to enable this material handling.

B.2.6.1 Granular Solids

Mechanical Pusher is defined here as the use of linear motion or a series or linkages to push granular solids. Reciprocating piston systems would be included here.

Auger / Screw Feeder systems are extensively used in industry for powders and discrete solids; existing COTS solutions merit terrestrial TRL 9 [387]. NASA has looked at ‘mechanical regolith mixing’ with augers and considered this to be TRL 3 for microgravity in 2015, noting that rotating seals and caking are perceived issues [152]. Also, an SBIR project by Grainflow Dynamics investigated flexible screws with arbitrary curvature for NEO applications in a lab test in 2011, considered TRL 3 [388]. More recently, applicable work on the HoneyBee Robotics Mobile In-Situ Water Extractor (MISWE) with its auger system are felt to merit raising the development status to microgravity TRL 4 [88].

Pneumatic conveying systems are well established in industry, with both compressed air (high-pressure) and vacuum (low-pressure) systems meriting terrestrial TRL 9 [389]. NASA has looked at ‘forced flow fluidization’ via air injection, and considered this to be TRL 3 for microgravity in 2015, noting that nozzle placement is an important design consideration to prevent clogging when off and even flow [152]. More recently in 2019, HoneyBee Robotics has prototyped pneumatic conveying systems or use with lunar regolith in the lab, thus meriting microgravity TRL 4 [154].

Rotating Feeder ('Airlock') is defined here as a series or chambers or doors that encourages motion in a certain direction. Note that one-way values could be in this category, but supplemental means to input energy would be needed to induce motion at a reasonable speed beyond random motion in a microgravity environment.

Electrostatic material handling systems utilize differences in electric charge to move particulate matter. A proof of concept for electrostatic particle transport of lunar regolith using traveling voltage waves between charged strips has been constructed by JAXA [390]. The transport and gather functionality demonstrated is felt to merit microgravity TRL 3.

N/A: A null option is permitted in this category, because some SoS may entirely avoid handling of granular solids. If processing options that only require fluid transport are selected granular solids handling is unnecessary; this occurs if volatiles are extracted in place from the regolith without removing it from the NEO using techniques such as 'optical mining'.

B.2.6.2 Fluids

Pressure Fed (by Heating) is defined here as the heating of a fluid to create pressure gradients along a path to induce motion. Experiments on the ISS are suspected to use this due to simplicity, with microgravity TRL 9 suspected.

Jet (momentum transfer) is the use of one fluid impinging upon another to push it in a particular direction.

Pressure Differential is defined here as the use of mechanical equipment like pumps to create induce pressure gradients along a path to induce motion. ISS equipment such as the Carbon Dioxide Removal Assembly (CDRA) include pumps, thus meriting microgravity TRL 9.

Flow Ionization is defined here as the use of electrical charges in a fluid with external applied electromagnetic fields to induce motion. Note that this could include pushing polar molecules with a sufficiently strong electromagnetic field, or creating ions by removing electrons to build up charge.

B.2.6.3 Work Input

Heating (Volume Increase) is defined here as an increase in thermal energy that increases the vapor pressure of a fluid, thereby inducing motion down a pressure gradient. A phase change is normally involved in this process, but not necessarily so. On Earth, fossil fuel power plants use a series of boilers to increase the steam pressure, meriting terrestrial TRL 9 [391]. On satellites, loop heat pipes are used to absorb heat in a wicking evaporator, then cool the working fluid in a radiator, to transport thermal energy in larger spacecraft [392]. The COTS nature of these solutions merits microgravity TRL 9.

Shaft Work (Pump, Blower, Auger) is defined here as energy input through contact forces by means of rotation about an axis. This is normally accomplished by a motor mounted on a shaft that drives another device that interacts with the media at hand, such as a pump (liquid) blower/fan (gas), or auger (granular solids). All three are widely used throughout terrestrial industry such as in food processing, meriting terrestrial TRL 9. Also, the ISS uses pumps to transport fluids throughout the structure, with more recent designs also utilizing pumps in microgravity, thus meriting microgravity TRL 9 [393], [394].

Linear Actuator is defined here as the use of linear motion or a series or linkages to impart kinetic energy. Reciprocating piston systems would be included here.

Compressor (Pressure) is defined here as the use of mechanical equipment like pumps to impart energy into a fluid or fluidized granular stream. ISS equipment such as the Carbon Dioxide Removal Assembly (CDRA) include pumps, thus meriting microgravity TRL 9.

Reference Frame (Spin) is defined here as the use of rotation of a body frame to induce motion in a direction. This should not be thought of as a centrifugal pump, but instead the spacecraft itself it that is spinning or a large chamber within it.

B.3 Indirect ISRU

Indirect ISRU is defined here as the set of functionality that is necessary to support ISRU activities, but not meaningfully interacting with the products produced. As per the functional decomposition in § 4.2: Functional Decomposition, the following functions have been identified: avionics, power generation, thermal management, waste management, and structures. Most of these systems stem from satellite design, with the exception of waste management which stems from mass conservation applied to ISRU.

B.3.1 Avionics

Avionics or data system refers to the command, control, and communication aspects of coordinating systems within a SoS. Note that effectors are not included here. One example of this is spacecraft control being relegated to be an aspect of active structures, due to possible attachment to the NEO. **Avionics** refers to the command 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.

B.3.1.1 Autonomy

Autonomous refers to the use of control logic on the local system to perform tasks where the decisions on which tasks to pursue made by the SoS locally, with a few permissible exceptions (e.g. remote troubleshooting). Both tactical and strategic decisions are made by the SoS on site.

Automated refers to the use of control logic on the local system to perform tasks, though the decisions on which overall goals to pursue are made remotely. Tactical decisions are made by the SoS on site, though strategic decisions are delivered using relayed commands.

Remote refers to the use of relayed commands from a ground station on Earth to dictate which tasks are performed by the SoS NEO ISPP. Neither tactical nor strategic decisions are made by the SoS on site. Note that limited autonomy is permitted on the local system, though initiating commands for tasks must come from Earth.

B.3.1.2 Computation

Centralized computation is defined here as designing a SoS to have data collected and sent to a set of co-located processors that process it, with commands sent back to systems as needed.

Distributed computation is defined here as a mesh of microprocessors that process data at the system or subsystem level and communicate with each other as needed.

String Isolated computation is defined as having a dedicated computer processor for each redundant copy of equipment at either the system or SoS (for isolated string redundancy) level.

B.3.1.3 Local Comms

Wired refers to the use of direct physical connections to transmit data. These connections can be wires within an operational unit, or tethered lines between operational units.

Transmitted refers to the use of wireless transmitters and receivers to send data via modulations of some portion of the electromagnetic spectrum.

B.3.1.4 Deep Space Comms

Powerful Radio (DSN) is defined here as the use of "steerable high-gain parabolic reflector antennas" to form a relatively direct link between the spacecraft(s) and responsible personnel on planet-side on Earth [395]. This definition explicitly includes the use of NASA's Deep Space Network (DSN) and comparable capabilities, meriting both microgravity TRL 9 [395]. The commercial use of geostationary telecommunications satellites by operators like Intelsat corporation similarly merits terrestrial TRL 9 [396].

Laser Link is defined here as the use of optical telecommunications with focused coherent light to transmit information between spacecraft(s) and responsible personnel on Earth. The successful operation of the Lunar Laser Communications Demonstration (LLCD) as part of the NASA Lunar Atmosphere and Dust Environment Explorer (LADEE) merits microgravity TRL 7 [397].

Repeaters or relays are defined here as a chain of transmitters to relay information between spacecraft(s) and responsible personnel on Earth. Though the telecommunications satellites deployed in the Iridium constellations have demonstrated the capability for cross-links between satellites, but they are not set up to receive communications from beyond earth orbit thus meriting microgravity TRL 6 [398]. The development of small satellite cross-link radios shows that this capability has been maintained over the years [54]. The use of Wi-Fi routers and internet of things smart hubs as relays in an analogous functional niche merits terrestrial TRL 9 [399].

An example of this would be spacecraft(s) in deep space communicating to telecommunications satellite relays at Earth-Sun Lagrange points. These relays could communicate with ground stations on Earth, or a constellation of satellites in Earth orbit which serve to boost the signal strength. The benefits of such an arrangement include fewer blind spots (i.e. spacecraft behind the sun), substantially increased bandwidth, and a reduction in the required transmitter and receiver signal strength on the spacecraft(s) of interest. Higher bandwidth and fewer communications outages would likely be extremely helpful for troubleshooting experimental complex ISRU SoS remotely, though inclusion of extra relay satellites would likely be cost prohibitive if relegated to a specific program.

B.3.2 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. Note that systems which handle non-electric energy such as heating, cooling, and optical systems are only included to the extent they require electrical power to operate. Secondary power systems may also be included, but are not considered here. **Energy Storage** refers to methods to store charge (esp. eclipsed PV) and/or smooth power demand (esp. batch processes). Note that material handling and command signals are excluded here due to consideration in other morphological groups. For electrical transmission (or power conduits), wiring using direct current (DC) is assumed to simplify the morph. matrix.

B.3.2.1 Electrical Generation

Concentrated Solar is the use of optics to focus sunlight to be harnessed as another form of energy. This other form of energy is typical electrical or thermal, depending on the use case. Utility scale concentrated solar power plants on earth tend to be thermal with an attached thermal gradient system, while smaller installations tend to use photovoltaic cells, meriting terrestrial TRL 9 [284]. In space, orbital beamed power satellites utilizing optics to focus sunlight on photovoltaic panels have been investigated for decades but have remained paper projects, with sources noting microgravity TRL 5 [400], [401].

Photovoltaic Cells use the band gap of semiconductors to generate electricity from photons absorbed within. This group of technologies sees widespread use today with silicon cells on earth with both residential and utility scale installations, meriting terrestrial TRL 9. In addition, high performance multijunction gallium arsenide cells are available COTS and power many commercial telecommunications satellites today, meriting microgravity TRL 9 [402].

Thermal Gradient methods use a heat engine to do work by moving thermal energy from an arbitrary hot body to an arbitrary cold body. Usually shaft power is produced by the heat engine, which is used to generate electricity in power plants and propel an automobile forward; this merits terrestrial TRL 9. Radioisotope thermoelectric generators are a type of thermal gradient that have flown on space missions from the Voyager probe to the Curiosity rover, but are excluded due to their use of radioactive materials [403]. Still, multiple thermal to electric conversion technologies exist such as Brayton cycles, Rankine cycles, Stirling engines, thermionic materials, and thermoelectric materials [74]. Unfortunately, only thermal gradient systems containing radioisotope thermoelectric generators have seen operation in space and these are excluded, which merits microgravity TRL 5 for an unintegrated system.

B.3.2.2 Energy Storage

Batteries are defined here as the storage of energy using charged molecules or ions. Note that only secondary cell chemistries are considered, due to the need to recharge batteries for periodic darkness.

Capacitors are defined here as the storage of energy through concentrated electric charge potential.

Chemical / Fuel Cell is defined here as the storage of energy in molecular bonds, or through the use of reversible chemical reactions. Note that flow batteries also fall into this category, due to the use of storage tanks for the reactants.

Thermal Mass is defined here as the storage of energy using the relative temperature of separated quantities of matter.

N/A: A null option is permitted in this category, because some SoS do not necessarily need to have energy storage. This is the case when constant uninterrupted sunlight and constant power demands can be assumed, as is applicable to large SoS NEO ISPP which completely envelop the asteroid.

B.3.3 Thermal

Thermal management refers to active methods by which the thermal energy of systems within the SoS is kept within permissible limits. This is done by heating and cooling the SoS as needed. Note that as the NEO progresses in its orbit it changes its heliocentric distance, and the NEO can also rotate to put the SoS NEO ISPP in its shadow as well. **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 means to do so. Extraction may also require high temperatures though it is excluded here, as it has a primary heating option included with high-power heating options. The main concern here is keeping electronics and mechanical components warm enough to operate. **Cooling** refers to methods to dissipate excess thermal energy to prevent overheating. **Heat Exchangers** refer to means to transfer thermal energy into, out of, and between fluids. **Distribution** refers to methods to transfer thermal energy from one location to another, within the SoS; this is sometimes termed the thermal bus or coolant loops. **Beam Transmission** refers to methods to transfer electromagnetic waves (primarily optical) throughout the SoS for radiative heating; this is especially used to route light to the cutting head. Different levels of sophistication permit different levels of interaction, such as active routing logic versus set pathways.

B.3.3.1 Heating [Secondary]

Focused Sunlight heating is defined here as the use of solar energy to increase the temperature of an object. This process can be passive by natural insolation, or actively encouraged by focusing sunlight upon a surface. Solar concentrators are often used for heating in plants on Earth and are even being used to help farming commercially, meriting a terrestrial TRL 9 [404]. In microgravity applications, the idea of solar concentrators was studied in the 1980's for space based solar power applications. Little development occurred in the ensuing years with a recent resurgence in interest for design concepts. Sercel et al. asserts that microgravity TRL 4 has been achieved [89].

Light (lamp/laser) heating is defined here as using coherent wavelengths of artificial illumination, focusing it for the purpose of increasing the thermal energy of a material. On Earth, lasers have been used to bend metal parts by mild diffusion of laser cutter beams in a process called laser induced thermal forming, or laser forming [285]. However the large heat affected zones and longer takt times characteristic of the process have limited its use to prototypes for niche applications, meriting terrestrial TRL 8 due to the lack of COTS solutions. For space applications, Laser Induced Breakdown Spectroscopy (LIBS) has been proposed as a sampling mechanism for interplanetary rovers, that works by vaporizing rock with a laser. Studies showing possible compact LIBS system designs have been published, along with test data from similar systems have been published in the literature, though for lower power lasers (e.g. 0.2 W) [286], [287]. Also worthy of note is research on planetary protection using laser ablation to generate thrust, with published tests of a 150 W laser beam on basalt [288]. Together, these research efforts merit microgravity TRL 4.

Resistance (Electrical) heating is defined here as the conversion of charge potential into thermal energy with the goal of increasing an object's temperature. This type of heating is very common in home heating systems, like electric hot water heaters and electric stovetop ranges, constituting terrestrial TRL 9. Small satellites like NASA Tracking and Data Relay Satellite System also often use electric heating systems to keep batteries warm with COTS solutions available, thus meriting microgravity TRL 9 [405].

Chemical Reaction based heating is defined here as utilizing exothermic transformations to substances to provide thermal energy to increase the temperature of an object. This method includes the use of thermal storage techniques that involve phase change as well as molecular reactions. But, this concept has not been well defined or even really explored for the microgravity environment due to its inherent use of consumables, and therefore is at microgravity TRL 1.

B.3.3.2 Cooling

Passive cooling refers to methods of redistributing thermal energy within the spacecraft that do not require non-thermal forms of energy as input to work. Capillary action, thermal conduction, heat pipes (exclusive of loop heat pipes), and passive louver designs to control thermal radiation are considered herein.

Radiators are systems that primarily reject heat through the emission of electromagnetic waves. These systems are used in many current satellite thermal systems, including the MarCO CubeSat among others, thus meriting microgravity TRL 9 [137]. Comparable solutions for radiative cooling on Earth are relatively experimental, with outdoor trials of cooling coatings to reflect sunlight meriting terrestrial TRL 4 [406].

Barbecue Roll is the periodic rotation of a spacecraft or some of its outside components to more evenly distribute radiative heating from sunlight; normally this is done for the whole spacecraft about the roll axis. This is considered an active thermal control system due to the requirement for a Reaction Control System (RCS) to be sized larger or a motor included to adjust the rate of rotation. This method of control is most often used when payloads are first exiting the atmosphere on rocket systems to keep temperatures down and has been used from the Apollo programs to more recent missions such as the GOES satellites, so the system has a microgravity TRL 9 [407]. This method of evenly distributing heat is used often in cooking techniques on Earth, such as rotisserie chicken, leading to a terrestrial TRL 9.

Heat Storage is defined here as an object that thermal energy is transferred into, that may or may not be cooled itself by other means. This includes thermal energy storage techniques and dumping heat into the NEO itself. One method of this storage is through phase change material plates on the outside panelling, which has been satellite-tested in Japan meriting a microgravity TRL 8 [408]. Phase change materials have also been investigated as a means to regulate temperatures in buildings, with review papers noting a few outside pilot building tests have been performed, thus terrestrial TRL 6 is presumed [409]. Phase Changing Material thermal control has also recently been tested on the in the Phase Change Material Heat Exchanger (PCM HX) Demonstration Facility, but results appear to be proprietary [410], [411]. Note that some forms of geothermal energy that alternate between heating and cooling at different parts of the year may be considered a form of thermal storage, though the longer timescales involved make speedy responses difficult [412].

Sublimation is the loss of material through phase change for the explicit purpose of reducing its temperature. This includes the use of evaporative cooling, transpiration, and liquid nitrogen baths. One such application is cooling magnets for Magnetic Resonance Imaging systems with solid nitrogen (~5 K), with subsystem tests meriting terrestrial TRL 5 [413]. In a microgravity environment, sorption coolers were launched on the ESA Hershel Space Observatory using the evaporation of superfluid helium-3 to cool sensors down to micro-Kelvin temperatures [414]. Published on-orbit measurements of this system merit microgravity TRL 8.

B.3.3.3 Heat Exchangers

Cold Plate heat exchangers are defined here as a flat or contoured surface with fluidic channels underneath, that is designed to transfer heat from the surface in to or out of the fluid. This includes mounting racks/plates cooled at the edges, and integrated tubing into a wall. Cold plates are quite common in space applications, with COTS options available as well as specialized versions available [415]. Also of note are ISS instruments, like the Ecosystem Spaceborne Thermal Radiometer on Space Station instrument built by NASA JPL, thus meriting microgravity TRL 9 [416].

Finned heat exchangers are defined here as an interface with markedly increased surface area via contorted geometry designed to increase convection into, out of, or between fluids. This includes protrusions (e.g. pins, fins) submerged in a fluid, and places where two fluid streams interface with complex geometry but do not mix their contents. Finned heat exchangers are commonly used in industrial air-based cooling solutions, with COTS solutions available garnering terrestrial TRL 9 [417]. These exchanger have also been used in spacecraft for years, such as the fins downstream of the nozzle in Joule–Thomson coolers and fins on the outside of heat pipes, meriting a microgravity TRL 9 [418], [419].

Tubular heat exchangers are defined here as places where two fluid streams interface on different sides of cylindrical walls, but do not mix their contents. Tubular heat exchangers are commonly used for heat regulation in oil refineries, meriting a terrestrial TRL 9 [420]. Since there is no gaseous heat sink available on spacecraft and multiple coolants are not typically used, tubular heat exchangers are generally restricted to niche low temperature sensor applications .

Phase Change / Cycle is defined here as a fluidic loop where a working fluid undergoes a phase change (and is latter changed back) in order to increase heat transfer rates. The thermodynamic cycles considered here are the only form of fluidic heat transfer that is able to transfer heat against a thermal gradient. These technologies are quite mature on Earth, with air conditioning units utilizing evaporators and condensers to manipulate the states of refrigerants, thus meriting terrestrial TRL 9.

N/A: A null option is permitted in this category, because some SoS may not require the enhanced rates of heat transfer that heat exchangers permit. If the anticipated magnitude of thermal energy above/below the specified operating range is sufficiently low that entirely passive thermal management systems can be used, heat exchangers are unnecessary. Note that any working fluids used for thermal management (e.g. heat pipes, loops) require the use of heat exchangers, while thermal conduction and louvers may not.

B.3.3.4 Thermal Distribution

Water Loop is defined here as the transfer of thermal energy from one object to another through closed fluid channels, using water as the working fluid. Water Loop is defined here as the transfer of thermal energy from one object to another through closed fluid channels, using water as the working fluid. There is currently a water loop in use on the ISS, indicating to a microgravity TRL 9 [421]. These systems are also commonly used in liquid cooled gaming computer systems on Earth, justifying a terrestrial TRL 9 [422].

Refrigerant Loop is defined here as the transfer of thermal energy from one object to another through closed fluid channels, using a chemical specifically selected to maximize thermal energy transfer. Note that loop heat pipes are refrigerant loops that do not require a pump for operation. Note that loop heat pipes are refrigerant loops that do not require a pump for operation. As the name suggests this is commonly used in refrigeration systems like refrigerators and air conditioners on Earth, leading us to a terrestrial TRL 9. An ammonia variation of this loop is used on the ISS in conjunction with the external radiators [421], [423]. In addition, the NASA Curiosity rover used a pair of Mechanically Pumped Fluid Loops filled with refrigerant-11 for heat rejection in both cruise and surface mission phases, thus meriting microgravity TRL 9 [424].

Heat Pipes are defined here as a long chamber closed at both ends containing a refrigerant, operating using a passive vapor cycle. On Earth, these systems are primarily used to redistribute thermal loads on electronic circuit boards, including gaming computer motherboards and aircraft avionics, thus meriting terrestrial TRL 9 for COTS solutions available [422], [425]. Heat Pipes also have a microgravity TRL 9 due to their common use on satellite systems, including the ISS and most modern telecommunications satellites [426].

Peltier Effect (Electrical) is defined here as the use of an applied voltage to transmit heat through a material. This technology is similarly used on Earth using on a smaller scale in portable personal cooling equipment such as seat covers, wristbands, and jackets for both heating and cooling, thus meriting a terrestrial TRL 9 [427], [428].

Thermoacoustics is defined here as the use of oscillating pressure differentials (acoustic waves) in a cavity as an intermediate to transform thermal energy into a more useful form of energy. Thermoacoustic heat engines operate by transforming thermal energy and/or electrical energy into sound, from which energy can be extracted by controlling the resonance and location of components. This field has had a recent breakthrough on Earth, with the development of the first-of-a-kind SoundEnergy THEAC-25 which uses resonant sound waves to cool using only input heat [429]. This device takes tens of kilowatts of heat at input temperatures of 160°C - 300°C, oscillates in argon gas pressurized to 12 bar, then cools a cavity to as low as -25°C with thermal efficiency of 40%-50% [429]–[431]. Waste energy is discarded as 70 dBa sound waves, and into a thermal sink at 30°C. Manufacturer test data and commercial installations currently underway are felt to merit terrestrial TRL 8.

For space applications, thermoacoustic devices have been prototyped for both cryocooling and electric generator applications. The Naval Postgraduate School launched the Space ThermoAcoustic Refrigerator (STAR) as an experiment on the Space Shuttle mission STS-42 in 1992, producing ~3 W cooling power using a 1 MPa helium-xenon resonator [432]. Researchers at the Los Alamos National Laboratory took a different approach, creating a proof of concept ThermoAcoustic Radioisotope Power Source (TARPS) attached to decaying plutonium 238, as an alternative to Radioisotope Thermoelectric Generators (RTGs) for space missions [433]. However, these designs were built decades ago with little development for space applications in the interim, thus it is felt that demoting this technology to microgravity TRL 3 is prudent.

B.3.3.5 Beam Transmission

Fiber Optics is defined here as a transparent filament with total internal reflection. High power fiber optic cables are used on Earth to form connections between laser sources and laser cutting systems mounted on robotic arms [434]. Specialized fiber optics are able to carry 20 kW in a single wavelength and 500 kW with multiple wavelengths of laser light, with their COTS nature meriting terrestrial TRL 9. For space applications, a prototype solar thermal system has been tested outside by Physical Sciences Corporation that used fiber optics to transmit the concentrated sunlight, meriting microgravity TRL 4 [210].

Mirrors refers to the use of lenses and reflectors to alter the properties of an electromagnetic beam in or close to the visible spectrum.

Beamed Microwaves refers to the use of lenses and reflectors to alter the properties of an electromagnetic beam with a wavelength significantly longer than near infrared.

N/A: A null option is permitted in this category, because some SoS do not use electromagnetic energy beam transmission. One such example of this occurs when inductive heaters are used instead of concentrated sunlight.

B.3.4 Wastes

Waste management refers to the end state of matter processed within the ISPP SoS that is not part of the desired quantity of propellant. These wastes take on a number of different forms, based upon the stage of the production process they are produced. Tailings refer to the part of the orebody that remains after the resource is extracted from the ore. Overburden is the excavated matter that is removed to access the resource bearing orebody. Byproducts refer to other chemicals that are produced by refining the ore into a consumable, other than the primary product that is. Excess refers to greater quantities of fuel or oxidizer produced than required by the return vehicle. Here, **Tailings & Overburden** comprise the end state for unwanted granular solids or powders produced. **Byproducts & Excess** comprise the ends state for unwanted fluids produced.

B.3.4.1 Tailings & Overburden

Eject into Space is defined as pushing granular solids away from the spacecraft and into outer space in some form.

Storage/Reuse is defined as holding onto the granular solids within the bounds of the spacecraft in some form. This could have the intent for more processing latter.

Deposit in Source is defined as taking the granular solids and attempting to put them back from whence they came (back into the NEO) in some form or another. A cover is likely needed to keep them in place.

Secure in Place is defined as holding onto the granular solids outside the bounds of the spacecraft in some form. A cover is likely needed to keep them in place.

B.3.4.2 Byproducts & Excess

Vent into Space is defined as using pressure differentials to disperse to push fluids away from the spacecraft and into outer space in some form.

Storage/Reuse is defined as holding onto the fluids within the bounds of the spacecraft in some form. This could have the intent for more processing latter.

Inject into Source is defined as taking the fluids and attempting to put them back from whence they came (back into the NEO) in some form or another. A cover is likely needed to keep them in place.

B.3.5 Structures

Structures refers to equipment designed to bear mechanical loads and maintain control of the spacecraft. Control is considered part of structures here due to the mechanisms required to keep a spacecraft anchored to a NEO being analogous to the telemetry, orbital determination, and altitude control functions of free-flying satellites. This need for an anchoring system for NEO operations is fairly unique for a space system, as most spacecraft are operated far from other spacecraft the majority of the time (rendezvous excepted), and most landers operate within a significant enough gravity well to provide a restoring force holding them in place.

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, in other words. **Relative Motion** refers to methods to reposition systems with respect to another body; change locations deliberately, in other words. **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.

B.3.5.1 Support Structure

Central Bus / Cylindrical is defined here as the use of common core to which other systems are attached. This common core is often a cylindrical fuel tank, in the case of geostationary telecommunications satellites. RUAG Space advertises the use of a ‘heavy core central cylinder’ on the ESA EarthCare observation satellite, thus meriting microgravity TRL 9 [435].

Truss / Space Frame refers to a set of interconnected beam members or struts that are primarily loaded in compression or tension.

Panel / Stressed Skin construction is defined here as the use of a structural shell where face sheets bear the majority of the loads. Semi-Monocoque construction also falls into this category, where the face sheets are reinforced using other means.

Floors / Support Decks refers to the stacking of systems on multiple levels in a common orientation, analogous to floors in a building. Stacks of circuit boards in a CubeSat lend themselves to this design.

Inflatable refers to pressurized gasses that are used to deploy then hold in place a deployed structure. Note that ‘balloon tanks’, such as those used on early Atlas rockets, that do not deploy and are merely stabilized by pressure are not included here. For terrestrial applications such as corporate events and traveling shows, a variety of self-supporting temporary inflatable structures have been designed and built [436], [437]. The range of designs from indoor walls to event halls, and the availability of COTS turnkey solutions merits terrestrial TRL 9.

When it comes to space applications, inflatable elements have historically been primarily investigated as reflectors for large space telescopes [438]. A technology demonstration mission named the Inflatable Antenna Experiment was tested in orbit on May 1996, with a partial deployment success of the 14 m diameter reflector resulting [439]. The three long struts and the torus deployed successfully, but the lenticular structure behind the mirror insufficiently tensioned it to function properly as an antenna reflector. These inflatable struts were later revisited for the NASA Asteroid Redirect Mission, with a one-fifth scale synched bag capture prototype tested [260]. Notably, this design used rigid joints between inflated members instead of stitched or welded fabrics. Taken together, these prototypes are felt to merit microgravity TRL 4, as seconded by Sercel [89].

B.3.5.2 Positioning

RCS Thrusters is the use of reaction control systems or orbital maneuvering systems to maintain position.

Inflatable Airbags is the use of expanding chambers filled with fluid to grab objects.

Harpoon / Anchor is defined as pushing an object into the NEO surface in some form to provide an object to pull back on.

Guy Wires / Tensegrity is defined here as the use of a network of tensioned cables to secure objects in place. This can be as simple as guy wires tied to one or more anchoring points, or a series of tensioned cables and nodes that envelop an object to secure it in place. This category also includes single or multiple slings around the NEO [80]. Tensegrity structures have been used on Earth for relatively lightweight stadium roofs, meriting terrestrial TRL 9 [440]. Networks of tensioned cables have also been proposed to envelop NEO to secure ISRU system elements in place [161]. Extensive analytical modelling has been preformed of for tensegrity structures in space, with breadboard tests of deployable tensegrity structures performed by industry, thus meriting microgravity TRL 4 [441], [442].

Microspines / Claw is defined as a mechanism that attempts to grip a surface by using protrusions. This can include appendages that wrap around an object or fine prongs that hold onto rough imperfections in the rock surface; both were considered as part of the NASA Asteroid Retrieval Mission [260]. Many ground tests were conducted with successive prototypes, with characterization data on system level tests meriting microgravity TRL 6 [443]–[445].

Friction with Excavator is a broad category that includes most situations where the excavation system is also tasked with anchoring. This can include augers drilling into NEO rock with more augers than are used for extraction at any one time, or burrowing systems ‘underground’ into the bulk of the NEO [100]. This can also include a drill that wedges itself into the rock and stops, expands its diameter like a rivet, pops out protrusions, or glues itself into place [80]. NASA JPL has tested a prototype “anchoring drill bit” which has teeth protrusions pop out to form a groove then remain engaged inside, meriting microgravity TRL 5 [445]. Note that this option could to require oversized or redundant excavation systems, since it is assumed that some excavation heads are required to be stationary to sufficiently arrest forces from active cutting activities.

Magnetic Pads is defined as the use of electromagnetic means to secure oneself to metallic objects.

Freezing Fluid is defined as injecting fluids into cracks with hopes that it will create mechanically strong tendrils or deposits that can be adhered to.

B.3.5.3 Relative Motion

RCS Thrusters is the use of reaction control systems or orbital maneuvering systems to maintain position.

Main Thrusters is defined as the use of spacecraft primary propulsion to maneuver to a new location. An example of this is hopping to a new location, like in HoneyBee Robotics' the World Is Not Enough (WINE) Cubesat Concept.

Robotic Joints is defined as the use of articulated limbs or linkages to maneuver. An example of this is the NASA InSight arm.

Cable Tension is defined here as the use of an actively controlled network of tensioned cables to permit relative motion of objects. This can be as simple as winching between static anchor points, or complex as manipulation of tensegrity structures. A variable length cable system called SkyCam™ has been used to move television cameras above the field of sporting events on Earth since the mid-1980's, meriting terrestrial TRL 9 [446]. Similar winching between static anchoring points has also been proposed for use on NEO [447]. Extensive analytical modelling has been preformed of for tensegrity structures in space, with prototypes of spherical tensegrity robots tested at NASA Ames, meriting microgravity TRL 4 [441], [448].

Internal Gas Jets are defined here as a collection of directed internal fluid bursts to locate one object inside of another. On Earth this is typically referred to as some sort of air levitation, but only one fluid jet is typically used due to the influence of gravity [449]. Due to the lack of fluid jets from multiple directions, this is rated terrestrial TRL 1. Open atmosphere air bearings are an example use case of this technology, but most systems are closer to cold gas reaction control systems as they exert external forces. Flow Space's Secure Handling by Encapsulation of a Planetesimal Heading to Earth–moon Retrograde-orbit Delivery (SHEPHERD) concept for NEO and debris transportation services is a novel approach to these ends. As only conceptual geometry has been published, this merits microgravity TRL 2 [261], [450].

B.3.5.4 Rotation Control

Selective Ablation is defined here as careful removal of NEO regolith using focused electromagnetic radiator or jets of matter designed to cause off-gassing and/or chunks to be released to provide torque on the NEO. Explicitly included here are laser ablation systems, focused sunlight, and firing rocket engines with the exhaust plume directed at the NEO.

Thruster Pods is defined here as the deployment of equipment that attaches itself to a NEO, then uses propulsive thrust to provide a torque upon the NEO.

Orbital Nudging is defined here as a carefully calibrated concert of NEO and spacecraft(s) trajectories such that unbalanced attractive forces are able to arrest rotation of a NEO. Note that the attractive force can come from electromagnetic fields or gravity, with this technique likely requiring an extremely small NEO mass to be workable.

Friction with Containment is defined here as putting components of the excavation system in contact with the NEO such that their rubbing together equalizes rotation between the spacecraft and the NEO, in as non-hazardous of a manner as possible.

Impactor is defined as releasing a projectile which is designed to hit the NEO in such a way that it arrests its rotation. The NASA Double Asteroid Redirection Test (DART) mission is intended to test this by launching in 2021 and impacting X-type Didymos B in 2022, meriting microgravity TRL 6 from the program being in detailed design at press time [451].

N/A: A null option is permitted in this category, because some NEO have a sufficiently low enough rate of rotation and negligible off-axis tumbling to make de-spin and de-wobble unnecessary. Alternatively, the spacecraft could align itself to the NEO axis of rotation and spin-up to match rotation with the NEO.

APPENDIX C. SIZING CODE RELATIONS

Additional documentation on the sizing code developed is provided herein, as a supplement to § 5.2. Note that not all identified functions were sized, as shown in Table 5-5. Example input and output formats are provided. Lists of secondary inputs with their default value and sources as appropriate are provided for each module. Verification studies to evaluate intermediate results at the module level are also discussed. To aid replication of results, an archived initial release of the source code used is available on Zenodo.

Source Code (CC BY 4.0): https://doi.org/10.5281/zenodo.3959262

C.1 Batch Handler

The batch handler (`doe_runner.py`) permits the execution of multiple cases of the SoS NEO ISPP model, using file input and output to support executing Design of Experiments (DoEs). There is no limit on the number of inputs supported, though unused inputs are flagged in the console after execution. The expected input form is a comma separated value (CSV) file with a header row of variable names (exact spelling required!), with case values on every subsequent row. The computed output is passed to a similarly formatted CSV file by default, with a pandas data frame optionally available. An example function call with condensed output is shown in § 0, with input data in Table C-1.

```
def run_doe(input_file, output_file='out.csv', overwrite='y', disp='s'):
```

C.1.1 Inputs for Batch Mode

- `input_file` - name of CSV file with variables & levels to be read [string] (DoE)
- `output_file` - desired name of output CSV file to be written to [string] (default = 'out.csv') Note - this will overwrite existing files
- `overwrite` - option to permit overwriting of variables in output dictionary (default = 'y') Options: {'n' - each instance has all variables from all modules, 'y' or any other string - duplicates replaced by last value seen}
- `disp` - option to display output; will do so if included [string] (default = None) Options: {None - no display (silent), 's'- start notices only, 'c' - condensed by case, 'y' or any other string - full print output}

Note that files are assumed to be saved in the same directory; sub directories can be specified by including '`os.path.sep`' or similar after the folder name. The CSV files should be formatted with a header row of variable names, with case values on every subsequent row. If exact spelling is not used (case matters), the input will not be used. If an input is not recognized, the default value will be used for optional inputs or case execution will stop with an error for required inputs. An example of a properly formatted CSV file is shown in Table C-1.

```
Case_ID,delta_v_mPs,t_days,D_min_AU,D_max_AU,period_NEO_h,prop_type
Ryugu_Steam,4646,100,0.963308,1.415893,7.63262,Steam
Bennu_Hydrogen,5087,100,0.896894,1.355887,4.296057,Hydrogen
3,3746.452408,79.87261017,0.889127666,1.143381389,10.58615276,Methalox
```

Table C-1: Example input CSV formatting in a text editor (top) and Excel (bottom)

Case_ID	delta_v_mPs	t_days	D_min_AU	D_max_AU	period_NEO_h	prop_type
Ryugu_Steam	4646	100	0.963308	1.415893	7.63262	Steam
Bennu_Hydrogen	5087	100	0.896894	1.355887	4.296057	Hydrogen
3	3746.452	79.87261	0.889128	1.143381	10.58615	Methalox

C.1.2 Outputs for Batch Mode

- `output_file.csv` - case results, written as CSV to provided '`output_file`' name. Note - this will overwrite existing files
- `results` - pandas data frame with case data (optional)

The output csv file will be structured with the same format as in Table C-1. The column order is as follows: input columns, key statistics, then all other stored variables sorted alphabetically by variable name (uppercase then lowercase). There should be the same number of rows in the output file as the input file. Note that the outputs are generated after all of the cases have been run; if a case fails the CSV file will not be generated but it may be possible to recover the dictionary intermediate that is being updated with each case execution. Note that disabling 'overwrite' will significantly increase the output file size, though it may be useful to check consistency between code modules. An example call of the case integrator upon Table C-1 with condensed output is shown on the next two pages.

```
results = run_doe('Table_C-1.csv', disp='c')


<<<Loading DoE>>>
Input File: Table_C-1.csv
Number of Cases: 3


<<<Executing Case: Ryugu_Steam>>>

---Provided Inputs---
Required Inputs:                    Related Quantities
        prop_type :     Steam       (270 s; 4.80E+05 W @ 50% eff.)
        delta_v_mPs :   4646 m/s    (fuel 31673 kg, ox 0 kg, pay 2000 kg)
        t_days :        100 days    (6.48E+06 s useable, 4.89E-03 kg/s)
        D_min_AU :      0.963 AU    (1466 W/m^2, 336 K)
        D_max_AU :      1.416 AU    (679 W/m^2, 277 K)
        period_NEO_h :  7.63 h      (1.37E+04 s working in darkness)
Optional Inputs:
        Case_ID :       Ryugu_Steam


---Overall SoS Totals---
SoS Totals: 1.49E+04 kg (30% margin), 4.99E+04 We, Heat 3.57E+04 Wt,
                    Cool 3.32E+04 Wt
Mass Payback Ratio: all 2.26 kg/kg, prop 2.12 kg/kg (3.37E+04 kg from
                    NEO, oversize 1.00, redundancy 1, Steam)
        Mass Fractions: Refine 0.06%, Extract 3.78%, Excavate 2.04%,
                    Storage 10.33%, Thermal 22.19%, Power 61.61%
        Mass Throughputs: Overall 2.83E-02 1/d, Refine 1.33E+01 1/d,
                    Extract 1.16E+00 1/d, Excavate 6.50E+01 1/d,
                    Storage 2.72E+00 1/d
Useful Prop: Regolith 14.27%wt (2.36E+05 kg excavated), Volatiles
                    84.1%wt (3.77E+04 kg evolved)
Power Mass Penalties: Electric 142 kg/kWe, Cool 75 kg/kWt, Heat 1.5
                    kg/kWt
        Specific Energy Intensity: 2.43E+07 J/kg (Electric 42%, Cool
                    28%, Heat 30%)
        Power Use Fractions: Refine 0.00%, Extract 38.98%, Excavate
                    5.50%, Storage 12.61%, Thermal 42.91%


<<<Executing Case: Bennu_Hydrogen>>>

---Provided Inputs---
Required Inputs:                      Related Quantities
        prop_type :     Hydrogen      (3000 s; 1.00E+05 W @ 70% eff.)
        delta_v_mPs :   5087 m/s      (fuel 1425 kg, ox 0 kg, pay 2000 kg)
        t_days :        100 days      (6.48E+06 s useable, 2.20E-04 kg/s)
        D_min_AU :      0.897 AU      (1692 W/m^2, 348 K)
        D_max_AU :      1.356 AU      (740 W/m^2, 283 K)
        period_NEO_h :  4.30 h        (7.73E+03 s working in darkness)
Optional Inputs:
        Case_ID :       Bennu_Hydrogen
```

```
---Overall SoS Totals---
SoS Totals: 5.44E+03 kg (30% margin), 2.04E+04 We, Heat 1.46E+04 Wt,
                    Cool 9.46E+03 Wt
Mass Payback Ratio: all 0.63 kg/kg, prop 0.26 kg/kg (3.42E+03 kg from
                    NEO, oversize 1.00, redundancy 1, Hydrogen)
        Mass Fractions: Refine 0.49%, Extract 4.12%, Excavate 2.49%,
                    Storage 20.11%, Thermal 19.46%, Power 53.33%
        Mass Throughputs: Overall 3.49E-03 1/d, Refine 1.21E+01 1/d,
                    Extract 1.17E+00 1/d, Excavate 9.21E-01 1/d,
                    Storage 1.57E+00 1/d
Useful Prop: Regolith 3.57%wt (9.60E+04 kg excavated),
                    Volatiles 9.4%wt (1.51E+04 kg evolved)
Power Mass Penalties: Electric 109 kg/kWe, Cool 84 kg/kWt,
                    Heat 1.5 kg/kWt
        Specific Energy Intensity: 2.02E+08 J/kg (Electric 46%,
                    Cool 21%, Heat 33%)
        Power Use Fractions: Refine 0.67%, Extract 41.76%,
                    Excavate 6.07%, Storage 4.72%, Thermal 46.78%


<<<Executing Case: 3>>>

---Provided Inputs---
Required Inputs:                   Related Quantities
        prop_type :     Methalox   (362 s; mix 3.40 vs. 3.99 stoch)
        delta_v_mPs :   3746 m/s   (fuel 1474kg, ox 5011kg, pay 2000kg)
        t_days :        80 days    (5.18E+06 s useable, 1.25E-03 kg/s)
        D_min_AU :      0.889 AU   (1721 W/m^2, 349 K)
        D_max_AU :      1.143 AU   (1041 W/m^2, 308 K)
        period_NEO_h :  10.59 h    (1.91E+04 s working in darkness)
Optional Inputs:
        Case_ID :       3

---Overall SoS Totals---
SoS Totals: 1.63E+04 kg (30% margin), 5.27E+04 We, Heat 3.76E+04 Wt,
                    Cool 3.45E+04 Wt
Mass Payback Ratio: all 0.52 kg/kg, prop 0.40 kg/kg (8.48E+03 kg from
                    NEO, oversize 1.00, redundancy 1, Methalox)
        Mass Fractions: Refine 0.29%, Extract 3.51%, Excavate 1.97%,
                    Storage 9.87%, Thermal 23.91%, Power 60.44%
        Mass Throughputs: Overall 6.65E-03 1/d, Refine 1.32E+01 1/d,
                    Extract 1.19E+00 1/d, Excavate 2.97E+00 1/d,
                    Storage 2.98E+00 1/d
Useful Prop: Regolith 4.31%wt (1.97E+05 kg excavated),
                    Volatiles 20.7%wt (3.13E+04 kg evolved)
Power Mass Penalties: Electric 144 kg/kWe, Cool 85 kg/kWt,
                    Heat 1.5 kg/kWt
        Specific Energy Intensity: 9.96E+07 J/kg (Electric 42%,
                    Cool 28%, Heat 30%)
        Power Use Fractions: Refine 1.42%, Extract 38.09%,
                    Excavate 5.47%, Storage 11.96%, Thermal 43.05%


<<<DoE Complete>>>
Computation Time: 4.680E-01 s (1.560E-01 s/case for 3 cases)
Output File: out.csv
```

C.2 Case Integrator

The case integrator sizes a single concept, calling modules and transferring data as needed. Output metrics described in § 5.3 are computed after other code modules finish execution. Example text output for hydrogen ISPP on Ryugu follows in § C.2.2.

```
class Master_ISPP __init__(self, delta_v_mPs, t_days, D_min_AU,
      D_max_AU, period_NEO_h, prop_type = 'Steam', **kwargs):
```

C.2.1 Primary Inputs & Modifiers

- `delta_v_mPs` - change in velocity required to return from NEO to LEO [m/s]
- `t_days` - time on station at NEO [days]
- `D_min_AU` - minimum heliocentric distance during mission (NEO perihelion for full orbit) [AU]
- `D_max_AU` - maximum distance from sun during mission (NEO aphelion for full orbit) [AU]
- `period_NEO_h` - time for NEO to complete one full revolution about its axis [h]
- `prop_type` - Propellant Type [string]; determines consumables produced through values like specific impulse & options like refining subsystems (Note: strings must come last in input line)

SoS Level Modifiers

- `redundancy` - Number of distinct sets of equipment for propellant production [int]; divides rate & multiplies mass (default = 1; Single String) [137]; passed to modules
- `margin_frac` - overall SoS mass margin, on top of system contingencies [%] (default = 0.3) Note: value propagates to system mass contingencies as their default [137]; passed to modules
- `cont__{MODULE}` - bare dry mass contingency for `{MODULE}` [%] (default = 0.3, or `'margin_frac'` if present) [137]; passed to modules
- `Case_ID` - identifier for which case was run [string]
- `disp` - option to display output after execution (default = None; no display); passed to modules

C.2.2 Example of Full Runtime Output

```
ISPP = Master_ISPP(delta_v_mPs = 4646, t_days = 100, D_min_AU = 0.9633,
D_max_AU = 1.4159, period_NEO_h = 7.63262, oversize = 1.1, redundancy =
3, prop_type = 'Hydrogen', disp = 'y') #Ryugu is nominal NEO here


<<<Initializing Case: Point Design>>>

---Provided Inputs---
Required Inputs:
        prop_type :     Hydrogen
        delta_v_mPs :   4646 m/s
        t_days :        100 days
        D_min_AU :      0.963 AU
        D_max_AU :      1.416 AU
        period_NEO_h :  7.63 h
Optional Inputs:
        oversize :      1.1
        redundancy :    3
        disp :          y

---Return Vehicle---
Propellant: Hydrogen, with Isp = 3000 s for delta_v = 4646 m/s
Mass Fractions - Propellant: 15.23%, Payload: 23.76%, Bare Dry: 61.02%
Masses - Fuel: 1282 kg, Oxidizer: 0 kg, Payload: 2000 kg,
                Bare Dry: 5137 kg (30% cont.)
Input Power: 1.00E+05 W, Radiators: 3.00E+04 W (70% engine eff.)
         Power: 2484 kg, Thermal: 117 kg, Engine: 500 kg, Other Dry
                Mass: 851 kg

---Rates---
Prop. Demand: Hydrogen   Fuel 1282 kg & oxidizer 0 kg
        Useful Time: 6.48E+06 s (75.0 days; 75% of 100 days at
                100% uptime)
Demanded Rates:          Fuel 2.18E-04 kg/s & oxidizer 0.00E+00 kg/s
Adjusted Demand:         Fuel 1410 kg & oxidizer 0 kg (fuel limited,
                oversize of 1.1)
Ambient NEO Temperature: 277 K at 1.42 AU (absorptivity 0.98,
                emissivity 0.90, beam param 1.8)

---Refining---
Demanded: Hydrogen       Fuel 1410 kg & Ox 0 kg in 75.0 days
                (redundancy of 3)
Electrolysis: H2 1410 kg (2.18E-04 kg/s), O2 11192 kg (1.73E-03 kg/s)
        1 cell(s) in stack (5.66E-01 kg, 1.78E+01 W)
        Tank:   Radius 0.090 m, length 0.007 m, with flat ends (0.00
                m^3 inside; mode r,L)
                Material: Ceramic (4.42E+07 Pa strength at 273 K),
                holding 1.01E+05 Pa
                Sized: 1.42E+00 kg, with wall 0.24 mm & end 6.09 mm
                thicknesses
        Tank:   Radius 0.038 m, length 0.261 m, with flat ends (0.00
                m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 273 K),
                holding 1.01E+05 Pa
```

```
                Sized: 1.43E-01 kg, with wall 0.03 mm & end 1.44 mm
                thicknesses
        Tank:   Radius 0.026 m, length 0.181 m, with flat ends
                (0.00 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 273 K),
                holding 1.01E+05 Pa
                Sized: 4.78E-02 kg, with wall 0.02 mm & end 1.00 mm
                thicknesses
        casing 1.42E+00 kg, buffer tank 1.43E-01 kg, dryer 4.78E-02 kg,
                pump 5.40E-01 kg
        Sized: 3.26E+01 kg, 2.78E+01 We, Heat 2.66E+02 Wt,
                Cool 0.00E+00 Wt; 3.89E-04 mol H2/h
Totals: 6.19E+01 kg (30% cont.), 2.78E+01 We, Heat 2.66E+02 Wt,
                Cool 0.00E+00 Wt
        Requested: H2O 12602 kg, CO2 0 kg

---Extraction---
Demanded: H2O 12602 kg & CO2 0 kg in 75.0 days
        NEO: H 2.02%wt (7.4 kg ore/kg H2O); C 3.22%wt (48.2 kg ore/kg
                CO2); S 5.25%wt (207.1 kg ore/kg SO2)
        Requested: Ore 9.31E+04 kg (1.44E-02 kg/s)
Thermal Vac: NEO ore 277 K, extraction to 1273 K, sorbent 308 K,
                desorbent 333 K
        Heat ore 8.58E+03 Wt, sublimate 5.61E+03 Wt, cool gases
                4.09E+03 Wt
        Tank:   Radius 0.145 m, length 1.003 m, with flat ends
                (0.07 m^3 inside; mode V,L/d)
                Material: Ceramic (4.42E+07 Pa strength at 1273 K),
                holding 1.01E+05 Pa
                Sized: 7.52E+00 kg, with wall 0.39 mm & end 9.81 mm
                thicknesses
        Tank:   Radius 0.154 m, length 1.066 m, with flat ends
                (0.08 m^3 inside; mode V,L/d)
                Material: Inconel (3.14E+07 Pa strength at 1073 K),
                holding 1.01E+05 Pa
                Sized: 2.63E+01 kg, with wall 0.59 mm & end 12.37 mm
                thicknesses
        Auger:  moving 4.35E-02 m^3/h (ID 1.46E-01m), length 1.00 m,
                with density 1190 kg/m^3
                Blade: thick 9.73E-03, pitch 1.46E-01 (140 RPM,
                3.22 m long, 2.50E-03 m^3)
                Sized: 19.66 kg, 24.04 We
        Chamber 34 kg (Hot Zone 8 kg, Wall 26 kg), Auger 20 kg
        Sized: 53 kg, 24 We, Heat 1.42E+04 Wt, Cool 4.09E+03 Wt
Extract: SO2 449 kg (6.94E-05 kg/s), from CO2 1933 kg & H2O 12602 kg
        Sized: 3.00E+00 kg, Heat 1.06E+02 Wt, Cool 1.06E+02 Wt
Filter: H2O 12602 kg (1.94E-03 kg/s) from from CO2 1933 kg
        Sized: 3.00E+00 kg, Heat -1.04E+02 Wt, Cool 0.00E+00 Wt
Totals: 2.16E+02 kg (30% cont.), 2.40E+01 We, Heat 1.42E+04 Wt,
                Cool 4.20E+03 Wt
        Requested: Ore 93070 kg

---Excavation---
Demanded: Ore 9.31E+04 kg in 75.0 days, & sample 2.00E+03 kg
                (50% as ore)
NEO: Regolith 1190 kg/m^3 at 50% porosity; 0% of regolith as overburden
                (1.00 kg regolith/kg ore)
```

```
Regolith Demanded: 9.51E+04 kg (1.47E-02 kg/s), 7.99E+01 m^3
                (4.44E-02 m^3/hr)
Corers: rate 1.1 mm/s, on 50% of time, cut energy 2.54E+08 J/m^3
                regolith (2.54E+08 J/m^3 ore)
        Sized: 10 kg, 334 We (Qty 8, running 7128 cycles each at
                42% kerf)
Totals: 1.04E+02 kg (30% cont.), 2.67E+03 We

---Storage---
Storables: O2 11192 kg, H2O 0 kg, CO2 1933 kg, SO2 449 kg
Hydrogen: fuel 1410 kg, ox 0 kg; solids 67 m^3
Oxygen (Liquid): 1.12E+04 kg (9.81E+00 m^3), Cool 7.93E+02 Wt
        Tank:   Radius 0.532 m, length 3.683 m, with ellipsoid ends
                (3.35 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 90 K),
                holding 1.01E+05 Pa
                Sized: 5.83E+01 kg, with wall 0.46 mm & end 0.46 mm
                thicknesses
Carbon Dioxide (Solid): 1.93E+03 kg (1.24E+00 m^3), Cool 1.01E+02 Wt
        Tank:   Radius 0.267 m, length 1.847 m, with ellipsoid ends
                (0.42 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 194 K),
                holding 1.01E+05 Pa
                Sized: 8.35E+00 kg, with wall 0.23 mm & end 0.23 mm
                thicknesses
Sulfur Dioxide (Liquid): 4.49E+02 kg (3.13E-01 m^3), Cool 3.17E+01 Wt
        Tank:   Radius 0.169 m, length 1.169 m, with ellipsoid ends
                (0.11 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 263 K),
                holding 1.01E+05 Pa
                Sized: 2.41E+00 kg, with wall 0.15 mm & end 0.15 mm
                thicknesses
Hydrogen (Liquid) - fuel: 1.41E+03 kg (1.99E+01 m^3), Cool 1.15E+03 Wt
        Tank:   Radius 0.673 m, length 4.659 m, with ellipsoid ends
                (6.78 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 20 K),
                holding 1.01E+05 Pa
                Sized: 1.15E+02 kg, with wall 0.58 mm & end 0.58 mm
                thicknesses
Solid Refuse (Tailings & Overburden): 6.72E+01 m^3
        Tank:   Radius 1.456 m, length 10.090 m, with ellipsoid ends
                (68.86 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 273 K),
                holding 1.00E+04 Pa
                Sized: 1.08E+02 kg, with wall 0.12 mm & end 0.12 mm
                thicknesses
Sample (Overburden): 8.40E-01 m^3
        Tank:   Radius 0.338 m, length 2.342 m, with ellipsoid ends
                (0.86 m^3 inside; mode V,L/d)
                Material: Stainless (1.38E+08 Pa strength at 273 K),
                holding 1.00E+04 Pa
                Sized: 1.59E+00 kg, with wall 0.03 mm & end 0.03 mm
                thicknesses
Sample (Ore): 8.40E-01 m^3
        Tank:   Radius 0.338 m, length 2.342 m, with ellipsoid ends
                (0.86 m^3 inside; mode V,L/d)
```

```
                Material: Stainless (1.38E+08 Pa strength at 273 K),
                holding 1.00E+04 Pa
                Sized: 1.59E+00 kg, with wall 0.03 mm & end 0.03 mm
                thicknesses
Totals: 8.61E+02 kg (30% cont.), Cool 2.08E+03 Wt

---Thermal---
Thermal Demand: Cool 6.27E+03 Wt & Heat 1.45E+04 Wt, with
                irradiance 1466 W/m^2
IR Lamps: heat 1.45E+04 Wt -> IR 1.76E+04 W (View 50%, reflecting 70%),
                req. cooling 3.10E+03 Wt
        Mass: 16.7 kg (qty 6, adj +20%; 1.2 kg/kWt)
Radiators: 9.37E+03 Wt, with incident flux 138 W/m^2 (Equl Temp 227 K)
        Panels: 190 W/m^2 rejected (Design Temp 285 K, Fin Eff 92.5%)
        Mass: 541.7 kg (8.8 kg/m^2, adj +25%), Area: 49.2 m^2
                (58 kg/kWt)
Totals: 7.26E+02 kg (30% cont.), 1.76E+04 We, Cool 3.10E+03 Wt
        Power Mass Penalties: Cool 75 kg/kWt, Heat 1.5 kg/kWt

---Power---
Power Demand: 2.03E+04 We, with irradiance 679 W/m^2
Photovoltaics: 5.66E+04 We (Eff Light 80% & Dark 65%, Eclipsed 50% of
                time)
        Panels: 158 W/m^2 (Eff 29.8%, Temp 290 K, derated irradiance by
                76.7%)
        Mass: 1251.0 kg (3.5 kg/m^2, adj +25%), Area: 357.4 m^2 (62
                kg/kWe)
Li-Ion: 1.59E+05 Wh (Eff 90%, DoD 60%), Discharging 3.82 h (50% of 7.6
                h period)
        Mass: 973.3 kg (qty 6422, adj +10%)
Totals: 2.89E+03 kg (30% cont.), Power Mass Penalty: 143 kg/kWe

---Overall SoS Totals---
SoS Totals: 6.32E+03 kg (30% margin), 2.03E+04 We, Heat 1.45E+04 Wt,
                Cool 9.37E+03 Wt
Mass Payback Ratio: all 0.52 kg/kg, prop 0.20 kg/kg (3.28E+03 kg from
                NEO, oversize 1.10, redundancy 3, Hydrogen)
        Mass Fractions: Refine 1.27%, Extract 4.45%, Excavate 2.14%,
                Storage 17.72%, Thermal 14.93%, Power 59.48%
        Mass Throughputs: Overall 2.70E-03 1/d, Refine 1.19E+01 1/d,
                Extract 9.23E-01 1/d, Excavate 2.76E-01 1/d,
                Storage 1.52E+00 1/d
Useful Prop: Regolith 3.45%wt (9.51E+04 kg excavated), Volatiles 8.6%wt
                (1.50E+04 kg evolved)
Power Mass Penalties: Electric 143 kg/kWe, Cool 75 kg/kWt,
                Heat 1.5 kg/kWt
        Specific Energy Intensity: 2.03E+08 J/kg (Electric 45.97%,
                Cool 21.25%, Heat 32.78%)
        Power Use Fractions: Refine 0.67%, Extract 41.74%,
                Excavate 6.05%, Storage 4.71%, Thermal 46.83%

Computation Time: 1.809E-01 s
<<<Case Complete: Point Design>>>
```

C.3 Propellant to Return

The return vehicle class computes the propellant mass required to complete the return trip from the NEO to LEO though the sizing of an in-space transfer stage. Note that several of the default values for secondary inputs used vary with propellant type, as per Table 5-3.

```
class Return_Vehicle __init__(self, delta_v_mPs, prop_type = 'Steam',
      **kwargs):
```

C.3.1 Secondary Inputs

Modifiers for Return Vehicle (All Propellant Types)

- `I_sp_s` - Specific Impulse [s], mass efficiency of propellant use
- `mix` - Mixture Ratio [%], oxidizer mass divided by fuel mass
- `m_eng_kg` - Propulsion system mass [kg], assumed equal to engine mass
- `m_samp_kg` - Regolith Sample Mass [kg] (default = 1 metric ton = 2000 kg)
- `m_comp_kg` - Returned Components [kg]; additional payload of ISPP equipment to be returned to LEO (default = 0 kg)
- `unuseable_frac` - fraction of propellant that is unable to be used [%] (default = 0.05 = 5%)
- `cont__ret_veh` - bare dry mass contingency for return vehicle [%] (default = 0.3, or `'margin_frac'` if present) [137]

Additional Modifiers for Return Vehicle (Continuous Thrust Only)

- `P_eng_W` - Total input power [W] (electrical: VASIMR or optical: STP) for continuous thrust engine
- `eta_eng_th` - Proportion of input power to engine that becomes thermal energy requiring dissipation outside engine [%]; *Hydrogen only*
- `eta_conc_th` - optical efficiency of light transmission [%] (default = 0.5 [20]) #Overall optical efficiency of 50% quoted; *Steam only*

  Note: same effect as `eta_eng_th` here, but permits same as power secondary input
- `m_optics_kg` - mass of optical mirrors, lenses, & supports utilized [kg] (default = 500.64 kg, [20] p.11)) #Telescoping tube assembly, includes large sapphire mirrors

Rates Module Iteration (Continuous Thrust Only)

- `flux_min_WPm2` - solar irradiation per unit area at maximum distance from sun (D_max_AU) during mission [W/m^2]
- `flux_max_WPm2` - solar irradiation per unit area at minimum distance from sun (D_min_AU) during mission [W/m^2]
- `T_amb_max_K` - ambient temperature of NEO at minimum distance from sun (D_min_AU) during mission [K]
- `t_days` - time on station at NEO [days]

C.3.2 Specific Impulse for Steam Thermal Propulsion

When it comes to steam thermal propulsion, significant disagreements exist in the field as to the achievable specific impulse. TransAstra's Omnivore concept is planning on $I_{sp} = 335$ s (@ $\mathrm{T_{ch}} \approx 2530\ K,\ P_{ch} = 68.9$ kPa), producing 100 N thrust with 250 kW optical power reaching the engine [11, p. 27], [89, pp. 2-52 (82)]. Quoted values from the company vary by source and material, with zirconia at 270 s $\leq I_{sp} \leq 335$ s and thorium oxide at 350 s $\leq I_{sp} \leq 400$ s [20], [89], [165]. A de-rated one dimensional kinematics performance model at chamber pressure of 100 psi ($P_{ch} = 68.9$ kPa) was also provided by TransAstra, and is shown with a blue curve in Figure C-1 [89, pp. 2-52 (82)]. The most optimistic design from TransAstra appears to anticipate a chamber temperature of $T_{ch} \approx 3300$ K (red crosshairs), with the most conservative design at $T_{ch} \approx 1820$ K (blue crosshairs). Note that some of these designs use a mixed gas stream of carbon dioxide as well as water, with increased thrust and efficiency at the detriment to specific impulse [89].

Other estimates of the performance of steam propulsion tend to be significantly lower, with reasonable independent estimates ranging from 155 s $< I_{sp} < 332$ s, primarily depending upon the temperature achieved by the thruster [211], [214], [452]–

[455]. This range of specific impulse is represented by the blue band in Figure C-1. Experimental testing of concentration optics have shown chamber temperatures generally in the range of $1088\text{ K} < T_{ch} < 2478\text{ K}$, with many designs around $T_{ch} = 1850\text{ K}$ [452]. This temperature range is represented by the red band in Figure C-1. Using the TransAstra performance curve, specific impulses of $190\text{ s} < I_{sp} < 330\text{ s}$ are predicted from this temperature range. Since the more conservative zirconium design from TransAstra (blue crosshairs) falls towards the middle of both the recorded temperature and specific impulse ranges from the literature, the default value of $I_{sp} = 270\text{ s}$ selected for steam propellant.

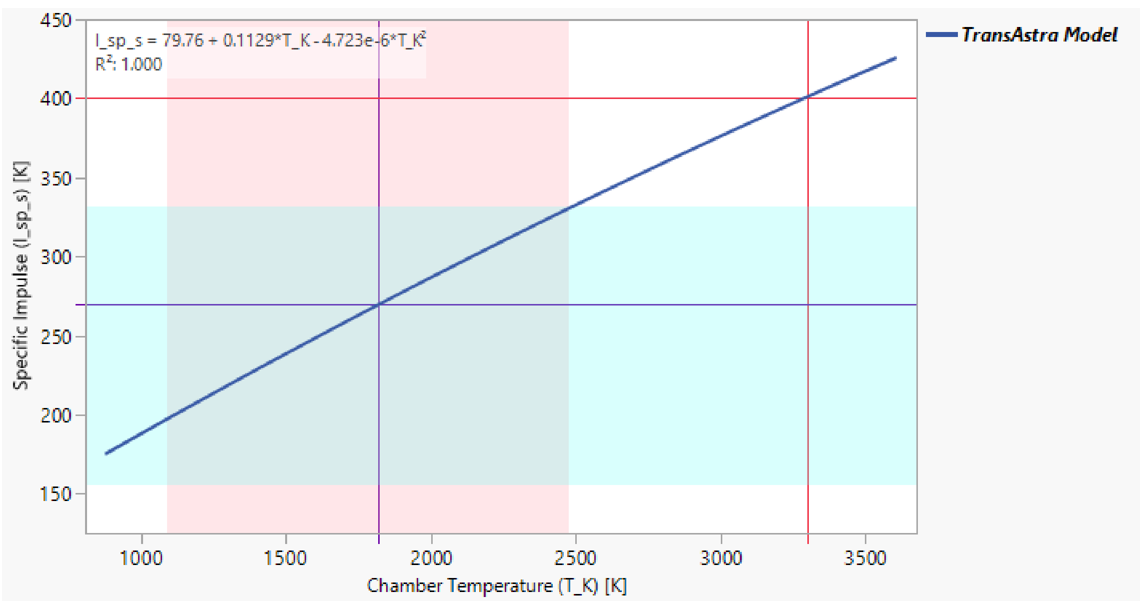


Figure C-1: Steam thermal propulsion specific impulse vs. chamber temperature. Crosshairs represent TransAstra Omnivore max. & min. performance estimates, with shaded ranges representing independent values from the literature.

C.3.3 Key Formulae

```
#Bare Dry Mass Breakdown
if prop_type in ['Steam','Hydrogen']:       #For continuous thrust
      m_dry_kg = (m_tanks_kg + m_avionics_kg + m_wiring_kg + m_eng_kg +
            m_shroud_kg + m_power_kg + m_thermal_kg) * (1 + cont_frac)
else:                                       #For impulsive thrust
      m_dry_kg = (m_tanks_kg + m_avionics_kg + m_wiring_kg + m_eng_kg +
            m_shroud_kg) * (1 + cont_frac)
#Bare Dry Mass Fraction - used to check for convergence
dry_frac = m_dry_kg / (m_dry_kg + m_pay_kg + m_prop_kg)

#Rocket Equation (1) implementation
m_prop_kg = (m_dry_kg + m_pay_kg) * (1 + unuseable_frac)
      * (np.exp(delta_v_mPs/(g_0_mPs2 * I_sp_s)) - 1)

#Fuel and Oxidizer from Propellant
m_fuel_kg = m_prop_kg / (1 + mix)
m_ox_kg = m_prop_kg * (mix) / (1 + mix)  #No Ox. for H2 & H2O, mix = 0
```

At the core of the return vehicle module is an implementation of Tsiolkovsky's Rocket Equation (1), solved for the difference between the initial and final masses. After a modifier for the unusable propellant fraction (default = +5%) is applied, this difference becomes the propellant mass required. The final mass has two main components: the payload mass, and the vehicle bare dry mass. The payload mass is a simple sum of two inputs, the NEO sample mass (default = 2000 kg = 1 metric ton), and the returned components mass (default = 0 kg) which accounts for ISPP equipment that is not left on the NEO. Two calculation modes are available for the bare dry mass of the transfer stage vehicle. If the dry mass is known it can be directly input, otherwise the bare dry mass fraction (default guess = 20%) is used to compute the bare dry mass, using an iterative loop with sizing relations of an orbital launch vehicle provided by Akin [177]. For continuous thrust propulsion (hydrogen and steam), the power and thermal modules are called for additional systems to be included in the bare dry mass. Photovoltaics are sized for hydrogen with solar concentrators based upon TransAstra's Honey Bee design are sized for steam, with both having radiators to dissipate excess heat [89]. Lastly, impulsive thrust bipropellants have the propellant mass split into fuel and oxidizer using a mixture ratio; continuous thrust monopropellants are considered to be all fuel.

C.3.4 Verification of Module

The main goal of verification for the return vehicle module was to ensure that the relative quantities of propellant demanded between propellant types were reasonable. A sample case was executed for each propellant type using inputs of Δv = 5000 m/s, m_{PAY} = 2000 kg, and 30% mass contingency, with sized values for the bare dry mass and propellant mass in Table C-2. Distributions of sized values from Figure C-2 bear out this trend. The two continuous thrust propellants (water & hydrogen) were observed to have greater bare dry mass than the impulsive thrust propellants (hydrolox & methalox), as desired. Propellant mass also increases as specific impulse decreases.

Table C-2: Bare dry mass and propellant mass sized by propellant for verification

Propellant Type	*Bare Dry Mass* (m_{DRY})[kg]	*Propellant Mass* (m_{PROP})[kg]	*Specific Impulse* (I_{sp})[s]
Hydrogen	5,178 kg	1,396 kg	3000 s
Water	4,557 kg	38,616 kg	270 s
Hydrolox	1,872 kg	8,248 kg	460.1 s
Methalox	1,644 kg	11,822 kg	362 s

Verifying the sized return vehicle bare dry masses proved more difficult, since the proposed propellants are not commonly used for in-space transfer stages due to concerns about storability. The one applicable return vehicle with enough information found to size for comparison was the TransAstra Honey Bee using water as its propellant. The craft appeared to be designed with a Δv budget of 290 m/s, 10^5 kg of ice as cargo, and specific impulse of 335 s [180]. Of the three values quoted for bare dry mass, 4714 kg was the middle estimate. With the same three inputs, the return vehicle module sized the bare dry mass at a comparable 4841 kg when no mass contingency was included in the design.

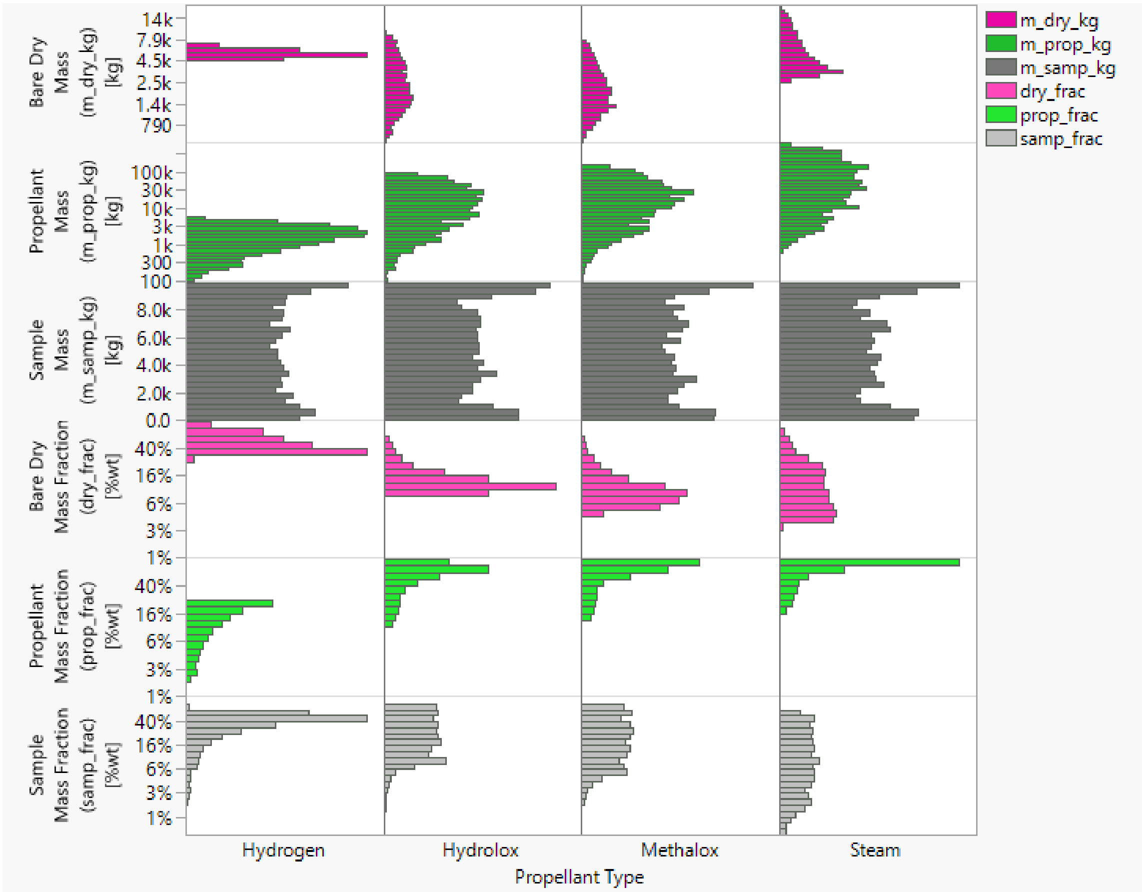


Figure C-2: Sized masses and mass fractions for both bare dry mass and propellant mass for return vehicles in experiment 2

C.4 Rate Adjustment

The rates module computes the expected average mass flow of propellant produced by the ISPP SoS, as well as average NEO temperature and insolation. This is done by applying a series of adjustment factors, like reducing the useful time on station to account for system setting up and shutting down.

```
class Rates __init__(self, m_fuel_kg, m_ox_kg, t_days, D_max_AU,
      D_min_AU, prop_type = 'Steam', **kwargs):
```

C.4.1 Secondary Inputs

- `redundancy` - Number of distinct sets of equipment for propellant production [int]; divides rate & multiplies mass (default = 1; single string [137])
- `oversize` - Multiplier for total mass flow rate [#]; (default = `redundancy`)
- `time_frac` - proportion of time on station available to produce propellant [%] (default = 0.75) # 25% of time assumed for setting up & shutting down
  - 10% for deployment & checkout (includes remote health checks, verification of system operation after deployment)
  - 10% for ramp up & down (equipment operates in sequence, neither simultaneous start nor shutdown)
  - 5% for loading return vehicle, & stowage of components (if applicable)
- `eclipse_frac` - Proportion of time plant is eclipsed in NEO shadow, or sunlight is otherwise too weak to be useable [%] (default = 0.5; half the time)
- `dark_opp_frac` - Proportion of time plant is operating during darker periods; uptime during subpar illumination [%] (default = 1; always operating)
- `light_opp_frac` - Proportion of time plant is operating during sufficiently high solar illumination [%] (default = 1; always operating)
- `abs_NEO` - absorptivity of NEO [frac] (default = 0.982, computed from Bold Albedo in [193] with relationship from [456]
- `emis_NEO` - emissivity of NEO [frac] (default = 0.9, for C-type Ryugu [193])
- `beam_param` - beaming parameter of NEO, accounts for surface roughness (decrease), thermal inertial (increase), & rotation (increase) (default = 1.8 for 2100 Ra-Shalom C-type [457]) Note: 0.6 < `beam_param` < 3.5 [458]

C.4.2 Key Formulae

```
#Useful Time for Propellant Production
t_s = t_days * 86400 * time_frac *
    (dark_opp_frac * eclipse_frac + light_opp_frac * (1 - eclipse_frac))

#Ambient Temperature (Run twice: min. then max.)
flux_WPm2 = 1360.8 * (1 / D_AU) ** 2               #flux_1AU_WPm2 [183]
T_amb_K = ((flux_WPm2 * beam_param * abs_NEO) /
      (emis_NEO * 5.67051E-8 * 4)) ** (1/4)      #boltzmann_WPm2K4 [137]
```

The minimum and maximum heliocentric distances during the mission are used to compute the sunlight reaching the NEO, and the estimated average ambient temperature of the NEO at those two locations. Note that if the mission is assumed to last a full orbit of the NEO around the sun or longer, the NEO aphelion is effectively the minimum heliocentric distance and the NEO perihelion is effectively the maximum heliocentric distance. The solar irradiance flux is computed using an inverse square law to scale a solar constant value of $1360.8\ \mathrm{W/m^2}$ at 1 AU [166], [183]. The radiative equilibrium temperature is then computed using equation 22-19 from *New SMAD*, adapted to include a beam parameter [137]. For this calculation, a spherical NEO is assumed in accordance with table 22-10 from *New SMAD* resulting in four times the emissive area versus absorbing area [137]. The C-type NEO absorptivity is assumed by default to be 98.2%, as computed from a Bond Albedo of 0.018 for Ryugu [193], [456]. The C-type NEO emissivity is assumed by default to be 90%, in line with assumptions for Ryugu [193]. The beam parameter is specific to NEO accounting for factors like surface roughness, thermal inertia, and rotation within an expected range of $0.6 < beam\_param < 3.5$ [458]. A default value of 1.8 is assumed in line with C-type 2100 Ra-Shalom [457]. The radiative equilibrium temperature computed using these factors is assumed to be the ambient NEO temperature. Note that this approximation ignores spatial variations within the NEO (esp. with depth), and temporal variation from diurnal cycles associated with rotation. The solar irradiance flux and ambient NEO temperature are computed for both the min. and max. heliocentric distance specified, and latter referenced by the extraction, thermal, and power modules.

The fuel and oxidizer masses are adjusted up to stochiometric levels ($mix_{methalox} = 3.9892,\ mix_{hydrolox} = 7.9367,\ mix_{steam} = 0,\ mix_{hydrogen} = 0$) on a mass basis, then multiplied by an oversizing adjustment factor. Note that these mixture ratios are among the few default values that are not editable via optional CSV inputs. This stochiometric condition is imposed in recognition that the water and carbon dioxide feedstocks extracted from the NEO are equivalent to ‘perfect combustion’ of the propellants. Since rocket engines tend to run fuel rich mixtures or use electric propulsion to improve specific impulse, this results in excess oxidizer being produced by the ISPP SoS, which is accounted for by the stochiometric condition. The oversize adjustment factor recognizes that one way to reduce mission risk is to size the ISPP SoS to produce more than the bare minimum propellant required by the return vehicle. The oversize factor is set equal to the global redundancy factor by default. Redundancy is implemented differently depending on the type of system being sized. In general redundancy is the minimum count for fixed value multiple instance systems. For scaled capacity systems redundancy divides the throughput then multiplies the mass to simulate multiple redundant systems of smaller size.

C.4.3 Verification of Module

The thermal equilibrium model was calibrated against Ryugu data, by tuning the beaming parameter to reasonable values. ESA’s Mobile Asteroid Surface Scout (MASCOT) was released by Hayabusa 2 onto the surface or Ryugu on 3 October 2018, recording its temperature for a 7.6 Earth hour diurnal cycle as shown in Figure C-3 to the left [187]. A maximum temperature of 302 K and a minimum temperature of 205 K were observed, at an estimated heliocentric distance of ~1.3 AU. The thermal radiative equilibrium model used in this work estimates an ambient temperature of 289 K at 1.3 AU as shown in Figure C-3 to the right. This was deemed a reasonable estimate, since it was quite close to the temperatures recorded by MASCOT on the light side of Ryugu.

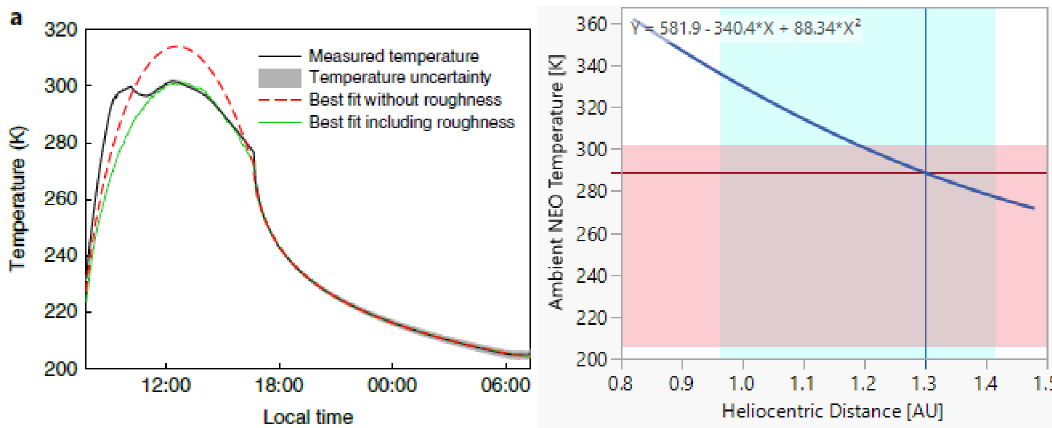


Figure C-3: Measured versus predicted ambient surface temperature for Ryugu. MASCOT data on left [187], was compared to thermal model fit on right. Blue shading is from Ryugu aphelion to perihelion, with line at MASCOT landing. Red shading denotes MASCOT temperature range, with line at model prediction.

Fits for the ambient NEO temperature and the solar irradiance versus heliocentric distance are in Figure C-4 for reference. Since modifiers upon the useful time for propellant production were not varied, a linear relationship is present. Distributions for the average propellant production rate by propellant type after adjustment are in Figure 6-11.

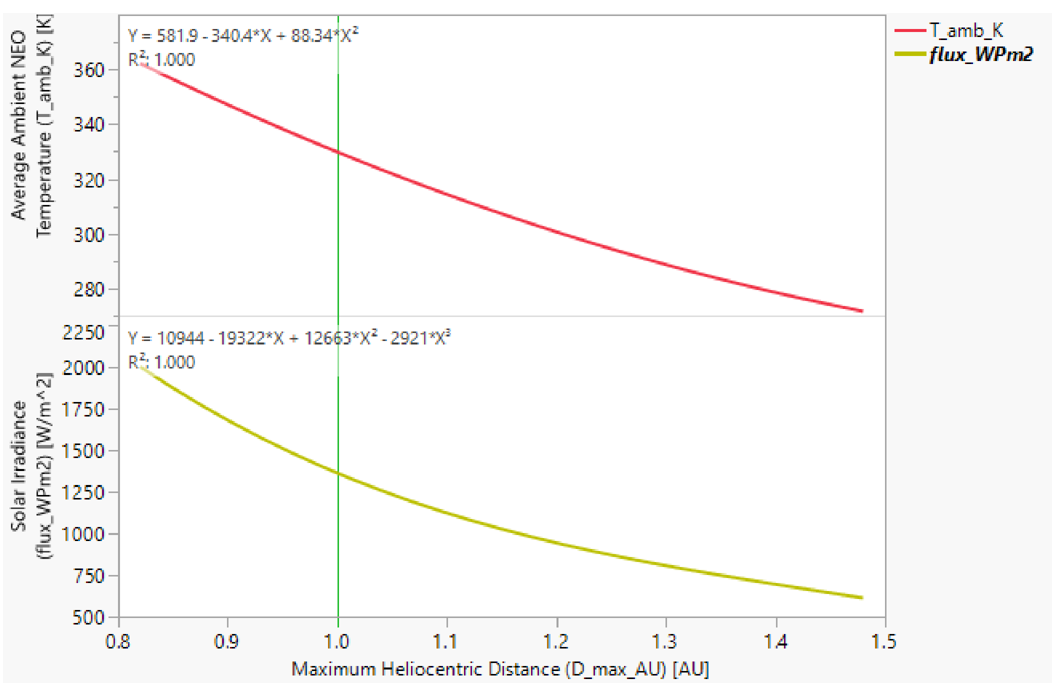


Figure C-4: Fits for average ambient NEO temperature and solar irradiance

C.5 Refining

The refine module is tasked with computing the mass of plant required to convert resources (water and carbon dioxide) into consumables (propellant).

```
class Refine __init__(self, m_fuel_kg, m_ox_kg, t_s, prop_type =
      'Steam', **kwargs):
```

C.5.1 Secondary Inputs & Set Values

- `HabNet` - Option to run unmodified HabNet Electolyzer & Sabaiter Sizing codes (default = None, only runs if HabNet == True)
- `T_filter_K` - filter temperature for processing carbon dioxide & water [K] (default = 358 K = 85 °C, Nominal PEM Electrolyzer Operating Temperature [459])
- `cont__refine` - Refining system mass contingency [%] (default = 0.3, or `'margin_frac'` if present) [137]

Electrolyzer Design Values

- `U_cell_V = 1.7` #Cell voltage (1.7 V nominal) [113]
- `current_density_APm2 = 25000` #Cell current density (25 kA/m^2) [113]
- `r_cell_m = 0.09` #Radius of electrolyzer cell [113]
- `t_bp_m  = 0.002` #Bipolar plate thickness (2 mm), titanium assumed [113]
- `t_gdl_m = 0.0012` #Gas diffusion layer thickness (1.2 mm), 60% porosity titanium [113]
- `t_pem_m = 0.0003` #Proton exchnage membrane thickness (.3 mm) - note: static areal density assumed by [113]
- `T_elec_K = 358` #85 °C Operating Temperature [459]
- `SEI_dry_JPkg = 1224000` #0.34 kWh_t / kg_H2: Dryer thermal load [460] p.15
- `P_pump_We = 10 * N_pumps` #Habnet selected pump had set power (10 W) [113]
- `m_pump_kg = 0.54 * N_pumps` #Habnet selected pump had set mass (0.54 kg) [113]
- `m_qual_kg = 5 * self.redundancy` #Quality Control Equipment - value taken from sum of sensors & valves in the TransAstra Honey Bee [89, p. Table 3-6]

Sabatier Reactor Design Values

- `R_channel_molPh = 0.102` #HabNet selected reactor set capacity (0.102 mol/h) [113]
- `m_chanel_kg = 1.75` #HabNet selected reactor had set mass (1.75 kg) [113]
- `A_chanel_m2 = 0.0002025` #HabNet selected reactor had set cross section (default 20.25 cm^2) [113]
- `l_pipe_m = 0.7` #Length of piping per reactor (default 70 cm) [113]
- `t_pipe_m = 0.0005` #Thickness of pipe (default 0.5 mm) [113]
- `fudge_pipe = 1.1` #fudge factor for other piping equipment (joints, bends, valves, connectors, etc.) (default = 1.1)
- `T_sab_K = 623` #350 °C "optimal average reactor operating temperature" [138]
- `eta_sab_frac = 0.90` #90% CO_2 conversion efficiency [138]
- `T_sep_K = 363` #90 °C assumed; implied condensation of liquid water at below ISS cabin pressure (<1 atm) for centrifugal pump used as phase separator [297], [298]
- `m_sep_kg = 10` #Another OGS Pump ORU cited at 23 lb (10 kg); actual mass UTC proprietary [461]
- `P_sep_We = 80` #Ground Test Prototype used 80 Watts for 103 kPa pressure rise [297]

C.5.2 Key Formulae

```
#Sabatier Reactor Mass (Only sized for methalox)
m_sab_kg = redundancy * (m_sab_kg + m_piping_kg + m_sep_kg + m_bt_kg)
      #Sabatier reactor, feed pipes, phase separator, buffer tank

#Electrolyzer Mass (Not Sized for steam)
m_elec_kg = 4 * redundancy * (m_elec_stack_kg + m_elec_casing_kg +
      m_elec_bt_kg + m_elec_dry_kg + m_pump_kg) #4 = HabNet Calibration
      #PEM cells, ceramic casing, buffer tank, dryer/dehumidifier, pump

#Quality Control Equipment Mass
m_qual_kg = 5 * redundancy #Several Flowmeters, thermocouples, & valves

#Aggregate System Sizing
m_kg = (1 + cont_frac) * (m_sab_kg + m_elec_kg + m_qual_kg)
P_We = (P_sab_We + P_sep_We) + (P_stack_We + P_pump_We)
Qc_Wt = (Qc_sep_Wt)
Qh_Wt = (Qh_sab_hx_Wt + Qh_recirc_Wt) + (-Q_elec_hx_Wt + Qh_dry_Wt)
```

The Proton exchange membrane (PEM) Electrolyzer and Sabatier reactor sizing codes were adapted from MIT's HabNet as described in the theses of Schrenk and Do [93], [113]. The main differences are the implementation of a more advanced pressure vessel sizing routine, energy use computed, and redundancy modifiers to set minimum instances. While HabNet used cylindrical tanks with fixed wall thicknesses, this work uses cylindrical tanks and computes wall thickness based upon the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC). Quality control equipment was also added based upon the sum of sensors & valves in the TransAstra Honey Bee [89].

C.5.3 Verification of Module

Sized masses of the PEM electrolyzer and Sabatier reactor were comparable to those in MIT's Habnet, though slightly lighter due to improved pressure vessel sizing. Refining system sizing was thus deemed adequate. Distributions for the refining systems sized as part of experiment 2 are in Figure C-5 for reference. Note refining system sizing had the greatest variability observed, with logarithmic scales on all axes in Figure C-5.

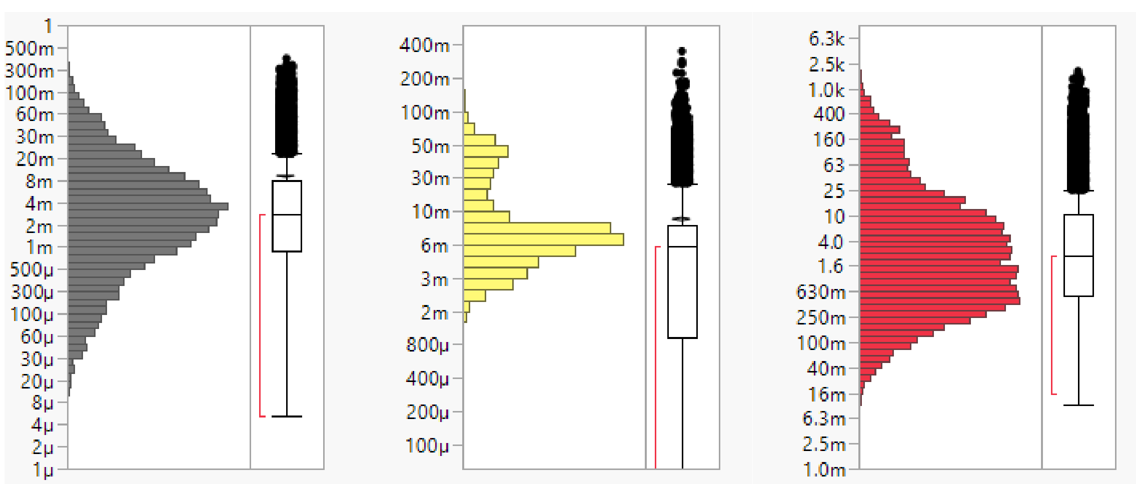


Figure C-5: Mass fraction (ζ_{REF}) [dec. wt.], energy use fraction (ξ_{REF}) [dec. en.], and mass throughput (f_{REF}) [1/day] distributions for refining system in experiment 2

C.6 Extraction

The extraction module sizes all the subsystems required to evolve the amount of volatile gasses required, and separates them sufficiently for refining to occur. The amount of NEO ore demanded is also determined from the amount of volatiles requested.

```
class Extraction __init__(self, m_H2O_kg, m_CO2_kg, t_s, T_amb_K,
      **kwargs):
```

C.6.1 Secondary Inputs

- `C_prop` - Mass fraction of NEO that is carbon atoms [%] (default = .0322; Orgueil in [151])
- `H_prop` - Mass fraction of NEO that is hydrogen atoms [%] (default = .0202; Orgueil in [151])
- `S_prop` - Mass fraction of NEO that is sulfur atoms [%] (default = .0525; Orgueil in [151]) - *largest impurity evolved is sulfur dioxide*
- `C_extract` - Process efficiency for extracting carbon atoms from NEO [%] (default = .176, computed from CI simulant heating data in [50])
- `H_extract` - Process efficiency for extracting hydrogen atoms from NEO [%] (default = .375, computed from CI simulant heating data in [50])
- `S_extract` - Process efficiency for extracting sulfur atoms from NEO [%] (default = .067, computed from CI simulant heating data in [50]
- `rho_ore_kgPm3` - Bulk density of ore, including voids from pores [kg/m^3] (default = `rho_reg_kgPm3`; 1190 kg/m^3, current estimate for Bennu & Ryugu [167], [186], [187])
- `porosity_frac` - Percent of regolith that is not occupied by solid mass; 'pores' in rock [%] (default = .50 = 50%; in range for both Bennu & Ryugu [167], [186], [187])
- `compaction_frac` - multiplier for porosity reduction from work done [%] (default = .0, no porosity reduction) - Note: .50 would half the porosity of the overburden, increasing its density

- `T_max_K` - gas evolution unit temperature; maximum temperature reached in extraction [K] (default = 1273 K = 1000 °C, CI simulant heating data upper bound in [50])
- `T_sorp_K` - sorption unit temperature for extracting carbon dioxide & water [K] (default = 308 K = 35 °C, CDRILS design value in [315])
- `T_desorp_K` - desorption unit temperature for releasing carbon dioxide & water [K] (default = 333 K = 60 °C, CDRILS design value in [315])
- `heat_ramp_KPmin` – rate of temperature rise of ore within vacuum furnace (default = 4 K/min [462])
- `vol_ther_vac` - additional volume multiplier for thermal vacuum chamber [%] (default = 0.2 = +20%)
- `L_D_ratio` - Length to diameter ratio for tanks [#] (default = 4)
- `cont__extract` - Extraction system mass contingency [%] (default = 0.3, or `'margin_frac'` if present [137])

C.6.2 Extraction Efficiency

When recovering resources from the natural environment, it is important to consider both the concentration of the resource in the ore and the proportion of the resource that can be reasonably recovered from the ore. Most sources discussing NEO ISRU focus on the former being NEO composition, with much less attention given to the latter, deemed extraction efficiency. Due to the differing minerologies present, changes from atmospheric reentry, and spectroscopy data available, elemental breakdowns were selected to be used to parameterize composition throughout this work.

In the absence of directly available measurements of NEO composition at press time (NASA OSIRIS-REx and JAXA Hayabusa 2 both ongoing), composition data on the Orgueil meteorite was used instead. Its composition includes 3.22%wt C, 2.02%wt H, and 5.25%wt S [151]. This decision was made since the carbonaceous chondrite 'CI' simulant developed by Deep Space Industries and the University of Central Florida that is the current state of the art at the time of publication mimics the Orgueil meteorite [176], [463]. This CI simulant (mark 2) is reported to have 3.85%wt C, 1.67%wt H, and 4.19%wt S [49], [151], [463].

This distinction between the meteorite and the simulant mimicking it is important, since the meteorite composition is likely more accurate, though evolved gas testing was conducted upon the CI simulant. To determine default values for extraction efficiency, thermogravimetry evolved gas analysis plots of the volatile release patterns of the CI simulant from 15 °C to 1000 °C in Figure 5-10 were first digitized [176]. The reported mass loss of 14.3%wt was then allocated among the volatiles proportionally after and integrating the individual curves for each evolved species via the trapezoid rule. It was noted that water (11.2%wt evolved; 78.2% of gas), carbon dioxide (2.48%wt; 17.3%), and sulfur dioxide (0.562%wt; 3.93%) accounted for over 99.5% of the gasses evolved. Oxygen was the next most common evolved species (0.0646%wt; 0.452%) followed by compound(s) with chemical formula C_3H_3 (0.0045%wt; 0.031%) digitized from a similar plot [50]. Thus, a decision was made to only consider H_2O, CO_2 and SO_2 as volatiles, ignoring all trace gasses.

Furthermore, it was assumed that elemental H, C, and S only evolved as H_2O, CO_2 and SO_2 respectively to further simplify the analysis. It was then postulated that there was a hypothetical ideal state where every hydrogen, carbon, and sulfur atom present in the NEO ore was evolved into water, carbon dioxide, and sulfur dioxide accordingly. Though sulfur is an undesired impurity, maximum recovery was still considered to be ideal to be consistent. By taking the weight percent of the evolved volatile gases from the CI simulant and dividing it by the corresponding values for this hypothetical ideal state, extraction efficiency was computed. The default values that resulted from this analysis are 37.5% of max H_2O per %wt H in ore, 17.6% of max CO_2 per %wt C in ore, and 6.71% of max SO_2 per %wt S in ore respectively. Since elemental oxygen tended to be present in excess of that required for this ideal state, its composition was left as a free variable and not tracked. Note that a large portion of this oxygen is probably tied up in metal oxides, as reflected by the extraction efficiencies computed falling well short of the hypothetical idea state.

It is suspected that values for extraction efficiency have some dependence upon both composition and temperature, though they were considered to be fixed to simplify the analysis. Though composition was varied, the extraction efficiencies were held constant to simplify the analysis. Though the lower bound on extraction temperature from NEO ambient temperature varies, the upper remains fixed in both experiments 1 and 2. Note that the maximum ambient temperature of 302 K (29 °C) at roughly 1.3 AU in Figure C-3 is very close to the starting temperature for heating the volatiles at ~ 308 K (35 °C) in Figure 5-10. Noting the relationship in Figure C-4, an ambient NEO temperature of 376 K (103 °C) is predicted at the lower limit of 0.75 AU for heliocentric distance in the design of experiments described by both Table 6-1 and Table 6-2. Based upon the curves in Figure 5-10, it is estimated that 0.41%wt H_2O (2.9% of evolved gasses) would be lost, effectively lowering the extraction efficiency by 3.8% to 36.1% of max H_2O per %wt H in ore in this worst case. Since this is was deemed a relatively minor loss, it was not accounted for in this sizing code intended for pre-conceptual design. More detailed models for latter project phases should consider accounting for this effect as a few sources have started to attempt to do, being listed as a topic for recommended future work in § 7.3 [50], [204].

C.6.3 Key Formulae

```
#Ore Demand Sizing
ore_per_H2O = 1 / (H_extract * (H_prop / 1.0078) * (2*1.0078 + 15.999))
ore_per_CO2 = 1 / (C_extract * (C_prop / 12.011) * (12.011 + 2*15.999))
m_ore_kg = max(m_H2O_kg * ore_per_H2O, m_CO2_kg * ore_per_CO2)
m_H2O_prod_kg = m_ore_kg / ore_per_H2O  #Similar for CO₂ & SO₂ produced

#Thermal Management
Qh_ore_Wt = C_P_ore_JPkgK * (T_max_K - T_amb_K) * m_dot_ore_kgPs
Q_sub_Wt = (L_sub_H2O_JPkg * m_H2O_prod_kg + L_sub_CO2_JPkg *
      m_CO2_prod_kg + L_sub_SO2_JPkg * m_SO2_kg) / t_s
Qc_vol_Wt = (T_max_K - T_sorp_K) / t_s * (C_P_H2O_JPkgK * m_H2O_prod_kg
      + C_P_CO2_JPkgK * m_CO2_prod_kg + C_P_SO2_JPkgK * m_SO2_prod_kg)
Qh_ext_SO2_Wt = (T_desorp_K - T_sorp_K) / t_s *
      (C_P_H2O_JPkgK * m_H2O_prod_kg + C_P_CO2_JPkgK * m_CO2_prod_kg +
      C_P_SO2_JPkgK * m_SO2_kg)
Qh_filter_Wt = (T_desorp_K - T_filter_K) / t_s *
      (C_P_H2O_JPkgK * m_H2O_prod_kg + C_P_CO2_JPkgK * m_CO2_prod_kg)

#Aggregate System Sizing
m_kg  = (1 + cont_frac)*(m_hot_zone_kg + m_ther_vac_wall_kg +
      m_ther_vac_aug_kg) * redundancy
P_We  = P_ther_vac_aug_We
Qh_Wt = Qh_ore_Wt + Q_sub_Wt + Qh_ext_SO2_Wt + Qh_filter_Wt
Qc_Wt = Qc_vol_Wt + Qh_ext_SO2_Wt
```

From a search of terrestrial analogs, a vacuum furnace was selected to evolve volatile gasses. These devices are commercially available with hot zones quoted up to 3000 °C, with built-in electrical heaters and vacuum pumps [184]. The furnace sized internal volume is computed using a NEO ore density (default = $1190\ \mathrm{kg/m^3}$ from Bennu and Ryugu regolith), and the takt time for the process [185], [186]. The takt time is computed from the temperature increase from NEO ambient at maximum heliocentric distance, along with a heating ramp rate (default = $4\ \mathrm{K/min}$) [462]. Internal volume is then sized by comparing this takt time to the available time for propellant production, along with the ore density and adjustments like the redundancy factor. An alumina ceramic shell with an Inconel casing slightly outside it are then sized using relations taken from the ASME BPVC. An auger to move the ore is also sized. To compute heating power the specific heat capacity of the ore at constant pressure along with the latent heat of sublimation for water, carbon dioxide, and sulfur dioxide (Table C-3) [187]–[190]. These quantities are then multiplied by their respective mass flows to arrive at the sized heating power. After exiting the vacuum furnace, the evolved volatiles are then cooled, with the cooling power similarly computed using the gasses' respective specific heat capacities at constant pressure.

Table C-3: Relevant Thermal Properties for Extraction

Substance Name	***Specific Heat*** **C_P [J/kg K]**	***Phase Change*** **L_{sub} [J/kg]**
Water	2,015	2,838,000
Carbon Dioxide	850	199,000
Sulfur Dioxide	960	420,000
NEO Ore	600	N/A

Next, the beneficiation subsystems are sized. Note that currently only the heating and cooling requirements for these units are sized, not their masses. To separate the bulk of the sulfur dioxide out of the gas stream, a series of pressure swing adsorption units are used, with a Z13X zeolite metal organic framework on the inside. This was done to reduce the propensity for sulfuric acid attack, as its formation is suspected at the high temperatures reached during thermal evolution. To separate the carbon dioxide from the water a series of ionic liquid absorption units are used, modelled after the Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) system in development for the ISS [315], [464].

C.6.4 Verification of Module

Volatile extraction of 11.2%wt water vs. ore from CI simulant (mark 2) with 1.67%wt H in ore was used to formulate the extraction efficiencies used. The model here predicts 13.5%wt water vs. ore recovered at 2.02%wt H in ore, corresponding to the black crosshairs in Figure C-6. Independent estimates of the CI simulant (mark 1) yielded 9.17%wt to 15.6%wt water from 2.04%wt H in ore, corresponding to the gray shaded region and vertical gray line in Figure C-6 [174], [204]. From this information, it is concluded that the evolved volatile content of the extraction module should be reasonable.

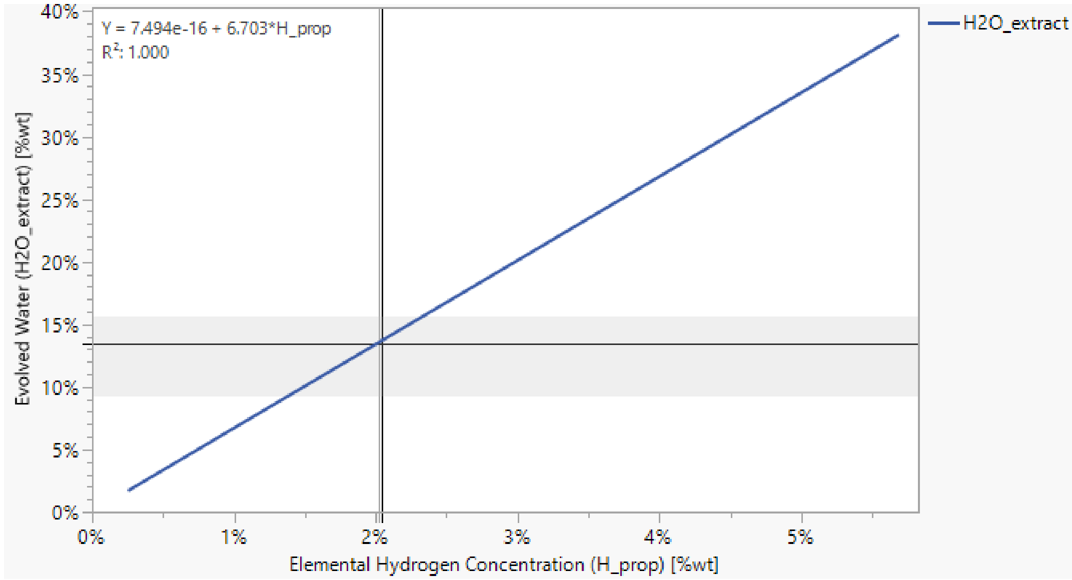


Figure C-6: Evolved water as a function of elemental hydrogen concentration in ore for experiment 2 (Note that `H2O_extract ≡ 1 / ore_per_H2O`). Black crosshairs are model at nominal case, with shaded region denoting values from literature [204]

Distributions for the extraction systems sized as part of experiment 2 are in Figure C-7 for reference. It is notable there are low mass fractions, but high energy use fractions.

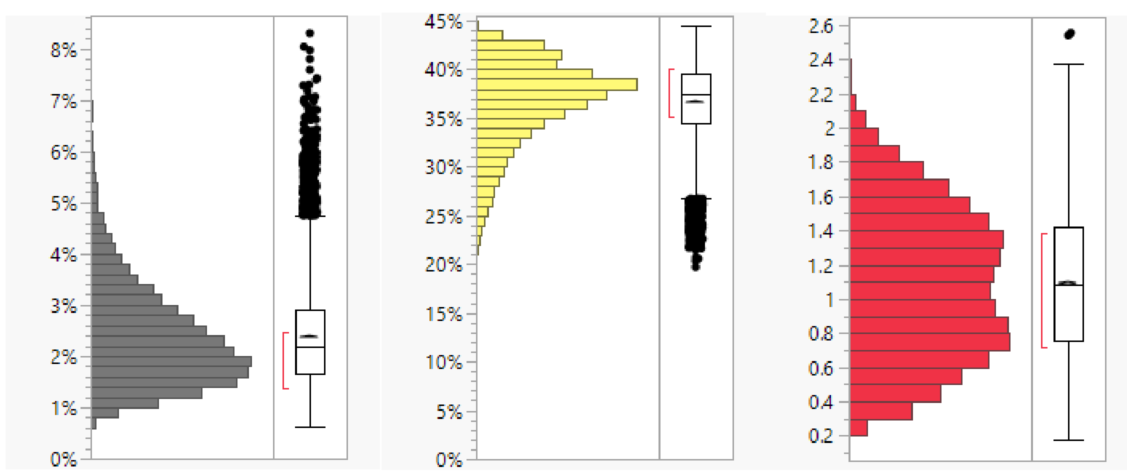


Figure C-7: Mass fraction (ζ_{EXT}) [%wt], energy use fraction (ξ_{EXT}) [%en], and mass throughput (f_{EXT}) [1/day] distributions for extraction system in experiment 2

C.7 Excavation

The excavation module computes the amount of regolith to be excavated to obtain the requested quantity of ore, and sizes the systems necessary to do so.

```
class Excavation __init__(self, m_ore_kg, t_s, **kwargs):
```

C.7.1 Secondary Inputs & Set Values

- `rho_reg_kgPm3` - Bulk density of regolith, including voids from pores [kg/m^3] (default = 1190 kg/m^3, current estimate for Bennu & Ryugu Ryugu [167], [186], [187])
- `rho_ore_kgPm3` - Bulk density of ore, including voids from pores [kg/m^3] (default = `rho_reg_kgPm3`)
- `porosity_frac` - Percent of regolith that is not occupied by solid mass; 'pores' in rock [%] (default = .50 = 50%; in range for both Bennu & Ryugu Ryugu [167], [186], [187])
- `compaction_frac` - multiplier for porosity reduction from work done [%] (default = .0, no porosity reduction) - Note: density increase from reduced porosity
- `overburden_frac` - Percent of regolith removed that is overburden, and not ore [%] (default = .0, homogenous asteroid (all ore) assumed [170])
- `m_samp_kg` - Regolith Sample Mass [kg], default is one metric ton (default = 1 metric ton = 2000 kg)
- `samp_ore_frac` - Fraction of sample that is ore, remainder is overburden (default = .50 = 50%; half & half)
- `cut_reg_JPm3` - energy required for cutting into NEO regolith, volume specific (default = 2.54E8 J/m^3, computed from corer annulus in [9].
  Note: range from 2E8 J/m^3 < `cut_reg_JPm3` < 5E8 J/m^3 for hard rock [275] p. 994
- `cut_ore_JPm3` - energy required for cutting into NEO ore, volume specific (default = `cut_reg_JPm3`).
- `corer_ROP_mPs` - rate of penetration of corer into rock (default = 0.0011 m/s = 1.1 mm/s [148])

- `corer_time_frac` - fraction of time that corer is coring into rock & requires power (defualt = 0.5 = 50%; half the time)
- `cont__excavate` - Excavation system mass contingency [%] (default = 0.3, or `'margin_frac'` if present) [137]

Corer Characteristics

- `L_core_m = 0.5` # 0.5 m [148]
- `d_core_m = 0.049` # 1.932" measured [147], 5 cm design [148]
- `d_bit_m = 0.0641` # 2.524" measured hole diameter [147]
- `m_corer_kg = 10` # 10 kg estimated; 16 kg for 1 m length & 2 kg for 10 cm length system [465]

C.7.2 Key Formulae

```
#Bulk Regolith Demand Sizing
m_reg_kg = (m_ore_kg + (m_samp_kg * self.samp_ore_frac)) * (1 / (1 -
      self.overburden_frac)) + (m_samp_kg * (1 - self.samp_ore_frac))
rho_over_kgPm3 = rho_reg_kgPm3 * porosity_frac / (porosity_frac * (1 -
      compaction_frac))

#Corer Sizing
cyc_per_corer = int(np.floor((t_s * corer_ROP_mPs * corer_time_frac) /
      (L_core_m)))                    #ore cores similar to overburden
N_cores_ore = np.ceil(V_ore_m3 / V_bit_m3 + V_samp_ore_m3 / V_core_m3)
N_corers = int(np.ceil((N_cores_over + N_cores_ore) / cyc_per_corer))
P_corers_We = V_kerf_m3 * (N_cores_over * cut_reg_JPm3 +
      N_cores_ore * cut_ore_JPm3) / (t_s * corer_time_frac)

#Aggregate System Sizing
m_kg  = (1 + cont_frac)*(m_corer_kg * N_corers)
P_We  = P_corers_We
```

The amount of regolith excavated is a sum of the NEO ore for resource extraction, the NEO overburden removed to access the ore, and samples from both. The goal here is to convert these masses into appropriate volumes. This is done by taking the mass of ore requested and computing the mass of overburden generated, with the samples allocated between them. Overburden density is then adjusted from the regolith for compaction. Densities are used to compute volumes, with adjustments made to differentiate pre-cut and post-cut volumes. Regolith is assumed to match C-types Bennu and Ryugu, with density

($1190\ \mathrm{kg/m^3}$) and porosity (50%) based upon gravimetry data from OSIRIS-Rex and Hayabusa 2 respectively [185], [186]. Asteroid formation theory postulates a fine heterogeneous mixture is present, thus a homogenous NEO where all regolith is equally good ore is assumed by default [170]. In this default case there is no overburden besides that of the requested NEO sample (default = 50% of 2000 kg), and no compaction of overburden occurs during excavation.

With volumes computed, the next step is to size the corer used to extract regolith. Corers were selected to reduce sample alteration during extraction, and minimize debris released from cutting. The corer was modeled using values from HoneyBee Robotic's The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) subsystem in their Planetary Volatiles Extractor (PVEx) system [147], [148]. Note that the heaters and condenser are not modeled herein, as the extraction module assumes heating to far higher temperatures. Each core is assumed to be 50 cm long and 4.9 cm in diameter, with the cut region extending out to a diameter of $6.41\ \mathrm{cm}$. The kerf from the cut is included in the excavated volume for the ore and overburden, but not for the samples. The number of cores drilled per corer is computed using the rate of penetration (default = $1.1\ \mathrm{mm/s}$), the proportion of time coring into the rock (default = 50%), and the time for propellant production [148]. The total number of cores to be drilled is then estimated using the volumes of ore, overburden, and both types of samples. From here the number of corers is decided upon, with the number greater than or equal to the global redundancy value. The corer power is then computed using the total number of cores cut, the kerf volume per cut, and the estimated cutting energy of both the ore and overburden. The cutting energy (default = $2.54 * 10^8\ \mathrm{J/m^3}$) was computed from test data for a similar smaller corer in development by HoneyBee Robotics for the Mars 2020 mission [191]. This approach was selected to permit modeling of ore and overburden of different mineralogy.

C.7.3 Verification of Module

The main aspect of the excavation module that was able to be verified was the corer power demand. The default value of cutting energy was computed based upon the corer design by HoneyBee Robotics within Mars 2020 sample caching system [191]. Using a 1.3 cm inner diameter, 2.2 cm outer diameter, 6 cm length, and peak bit power of 15 W for a 251 s cut, a cutting energy of $2.54 * 10^8\ \mathrm{J/m^3}$ was computed for the annulus. For the larger HoneyBee TRIDENT corer, power levels of 105 We to 180 We were observed in tests, with a maximum rated power of 187 W [148]. This agrees well with the single corer power of 187 We computed using the default values for the excavation module.

Distributions for the excavation systems sized as part of experiment 2 are in available in Figure C-8. Mass and energy use fractions tended to be moderate compared to other sized systems, except when high overburden and low hydrogen concentrations were used.

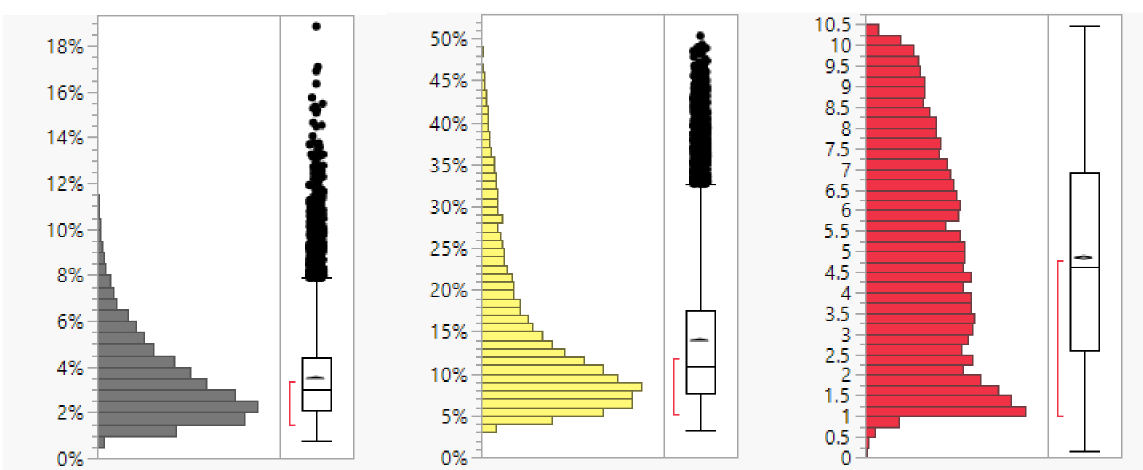


Figure C-8: Mass fraction (ζ_{EXC}) [%wt], energy use fraction (ξ_{EXC}) [%en], and mass throughput (f_{EXC}) [1/day] distributions for excavation system in experiment 2

C.8 Storage

The storage module computes mass of containers for all intended consumables and wastes produced by the ISPP SoS. It is assumed that all waste products (excess, byproducts, tailings, and overburden) are stored to attempt to maintain a more benign space environment in the vicinity of the NEO and avoid negative impacts on other systems. Note that nearly all inputs have been set as optional inputs, to allow flexibility in what is being sized for storage. If a mass is not passed into the class, a pressure vessel will not be sized. Relevant thermal properties used for densification for storage are in Table C-4.

```
class Storage __init__(self, t_s, **kwargs):
```

C.8.1 Secondary Inputs

- `m_O2_kg` - mass of excess oxygen provided [kg] (default = 0 kg)
- `m_H2O_kg` - mass of excess water [kg] (default = 0 kg)
- `m_CO2_kg` - mass of excess carbon dioxide [kg] (default = 0 kg)
- `m_SO2_kg` - mass of excess sulfur dioxide [kg] (default = 0 kg)
- `m_fuel_kg` - mass of fuel; type set by [kg] (default = 0 kg)
- `m_ox_kg` - mass of oxidizer [kg] (default = 0 kg)
- `V_solids_m3` - volume of solid wastes: tailings & overburden [m^3] (default = 0 m^3)
- `V_samp_reg_m3` - volume of regolith samples to excavate [m^3] (default = 0 m^3)
- `V_samp_ore_m3` - volume of ore samples to excavate [m^3] (default = 0 m^3)
- `prop_type` - Propellant Type (string) (default = 'Steam')
- `P_Pa` - Design pressure for storage [Pa] (default = 101315 Pa = 1 atm)
- `T_K` - Supply Temperature, overrides defaults for other temperatures if given [K]
- `T_in_O2_K` - Inlet temperature for Oxygen (default = 358 K = 85 °C, Electrolyzer Operating Temperature [459])
- `T_in_CO2_K` - Inlet temperature for Carbon Dioxide (default = 358 K = 85 °C, PEM Filter; assuming same as Electrolyzer Operating Temperature)

- `T_in_SO2_K` - Inlet temperature for Sulfur Dioxide (default = 333 K = 60 °C, Desorption unit temperature, CDRILS design in [315])
- `T_in_H2O_K` - Inlet temperature for Water (default = 358 K = 85 °C, PEM Filter; assuming same as Electrolyzer Operating Temperature)
- `T_in_CH4_K` - Inlet temperature for Methane (default = 623 K = 350 °C, "optimal average reactor operating temperature" [138])
- `T_in_H2_K` - Inlet temperature for Hydrogen (default = 358 K = 85 °C, Electrolyzer Operating Temperature [459])
- `cont__storage` - Storage system mass contingency [%] (default = 0.3, or `'margin_frac'` if present [137])

Tank Sizing in Storage

- `P_Pa` - internal design pressure of tank (default = 101325 Pa = 1 atm)
- `T_K` - temperature walls are exposed to, in Kelvins [K], used to calculate critical stress value (default = 273 K , freezing)
- `joint_eff_frac` - ASME joint efficiency; 1 for full NDTE weld inspection, 0.85 for partial (default = 0.85)
- `attach_frac` - additional mass for miscellaneous attachments, as function of tank mass (default = 0.2 = 20% extra mass)
- `ends` - geomertry option for end cap of cylinder ('ellipsoid' used in storage; default = 'flat', flat head); supported: {'flat', 'ellipsoid', 'sphere'}
- `material` - tank wall material (default = 'Stainless' Steel); supported: {'Stainless' [AISI 316Ti], 'Al' [6061 T6], 'Ti' [Grade 12], 'Inconel' [N06230], 'Ceramic' [Alumina AL98]}

Primary inputs for Tank Sizing (provide two of four; preference in this order)

- `r_m` - tank radius [m]
- `L_m` - tank length [m]
- `V_m3` - internal volume of tank [m^3] (default = 1 m^3, only assigned if solely `L_D_ratio` input); storage provides value
- `L_D_ratio` - Length to diameter ratio of tank [#] (default = 4, first assigned if insufficient inputs given); storage uses value

C.8.2 Key Formulae

```
#Oxygen Storage Example
(m_store_O2_kg, V_O2_m3, Qc_O2_Wt) = chilled_tank(m_kg = self.m_O2_kg,
      T_K = T_vap_O2_K, T_in_K = T_in_O2_K, rho_kgPm3 = rho_O2_kgPm3,
      C_P_JPkgK = C_P_O2_JPkgK, L_JPkg = L_vap_O2_JPkg, name = 'Oxygen
      (Liquid)')

<<In chilled_tank()>>
Qc_Wt = (C_P_JPkgK * (T_in_K - T_K) + L_JPkg) * m_kg / self.t_s
m_tank_kg = Tank_cyl(V_m3=V_m3/ redundancy, P_Pa= P_Pa, T_K=T_K,
      ends='ellipsoid', disp=Disp) * redundancy

<<In Tank_cyl()>>    #(6) Volume & L/D ratio, stainless, ellipsoid ends
L_m = L_D_ratio * np.cbrt(3 * V_m3 / (4 *np.pi))        #Length estimate
r_m = np.sqrt(V_m3/(L_m*np.pi))              #Guesses equivalent cylinder
t_bod_m = P_Pa*r_m/(stress_max_Pa*joint_eff_frac - 0.6*P_Pa)
t_end_m = 2 * P_Pa * r_m /(2 * stress_max_Pa * joint_eff_frac - 0.2 *
      P_Pa)                     #2:1 Ellipsoidal ends, ASME BPVC VIII-1
m_tank_kg = rho_kgPm3 * (((L_m - r_m * 8/16) * np.pi * ((r_m + t_bod_m)
      ** 2 - r_m ** 2)) + (t_end_m * np.pi * r_m * (1 + 1/42 +
      0.0567))) * (1 + attach_frac)       #Calibrated to be slightly big

#Aggregate System Sizing
m_kg  = (1 + cont_frac)*(m_store_soild_kg + m_store_O2_kg +
      m_store_H2O_kg + m_store_CO2_kg + m_store_SO2_kg + m_store_ox_kg
      + m_store_fuel_kg + m_store_samp_over_kg + m_store_samp_ore_kg)
Qc_Wt = Qc_O2_Wt + Qc_H2O_Wt + Qc_CO2_Wt + Qc_SO2_Wt + Qc_ox_Wt +
      Qc_fuel_Wt
```

Input preferences for tank sizing (first legal set used):

1. Given radius & length (used in refining)
2. Given radius & length to diameter ratio
3. Given length & length to diameter ratio
4. Given radius & volume
5. Given length & volume
6. Given volume & length to diameter ratio (used in storage, extraction, & refining)

Table C-4: Relevant Thermal Properties of Chemical Species for Storage

Chemical Species	*Input* T_{in} [K]	*Chilled* T_{store} [K]	*Densified* ρ [kg/m^3]	*Phase Change* L [J/kg]	*Specific Heat* C_P [J/kg K]
Oxygen	358	90	1141	213,000	918
Carbon Dioxide	358	194	1562	199,000	846
Sulfur Dioxide	333	263	1434	389,640	960
Water	358	273	917	2,838,000	1,864
Methane	363	111	423	511,000	2,226
Hydrogen	358	20	71	461,000	14,310

C.8.3 Verification of Module

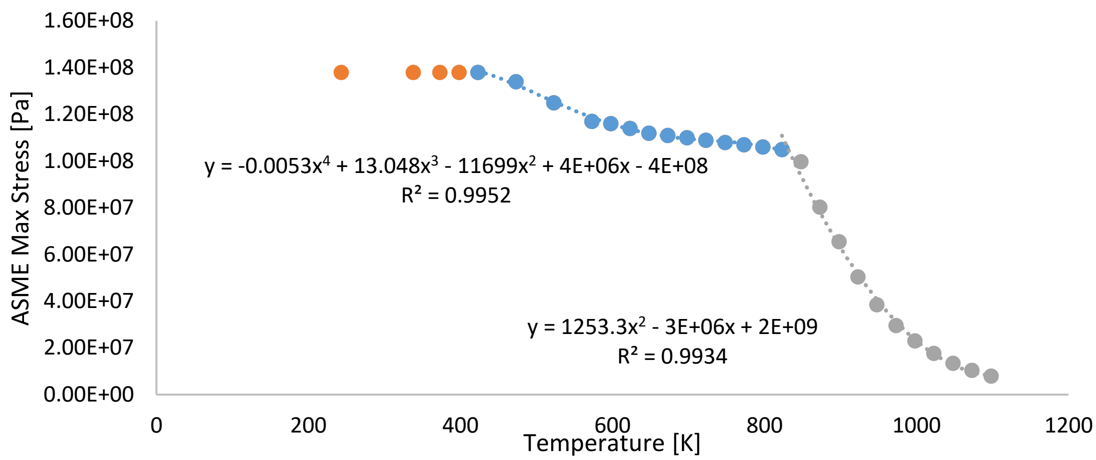


Figure C-9: ASME Allowable Stress Regressions for AISI 316Ti (Russian Stainless)

The storage module as a whole was not able to be verified directly, since cryogenic propellants are not typically stored with cooling systems on spacecraft for long durations. Instead, efforts were made to make the pressure vessel sizing fidelity relative to other modules. Example code output is in § C.2.2, with a sample set of regressions for allowable stress temperature regression based upon ASME Code limits in Figure C-9. Distributions for the masses stored by propellant type are shown in Figure C-11 for reference.

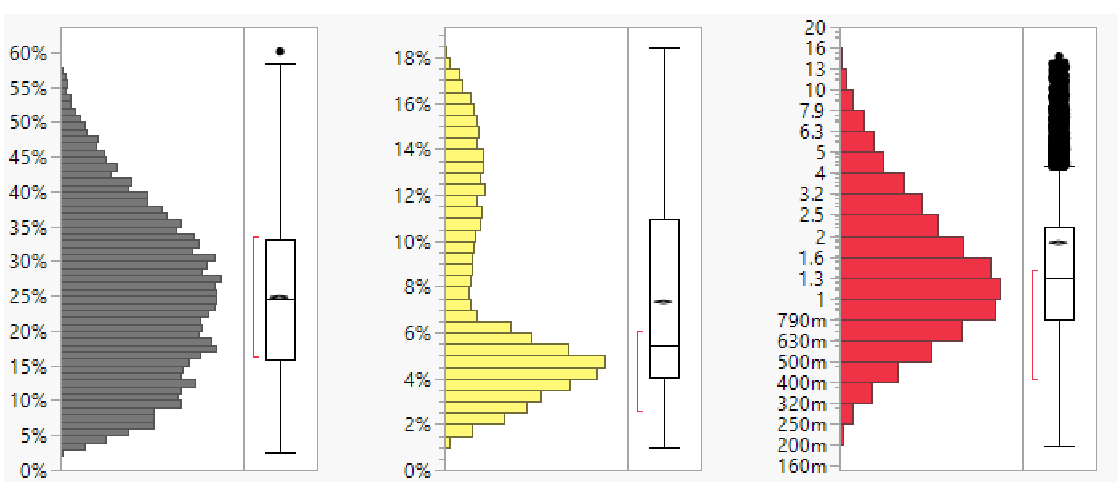


Figure C-10: Mass fraction (ζ_{STO}) [%wt], energy use fraction (ξ_{STO}) [%en], and mass throughput (f_{STO}) [1/day] distributions for storage system in experiment 2

Distributions for the storage systems sized as part of experiment 2 are in Figure C-10 for reference. Mass fractions distributions for storage appear to be relatively propellant agnostic, along with mass throughput. For the storage energy use distributions though, there is a marked difference between the greater values with greater spread from methalox and steam, with lesser values and lesser spread from hydrolox and hydrogen.

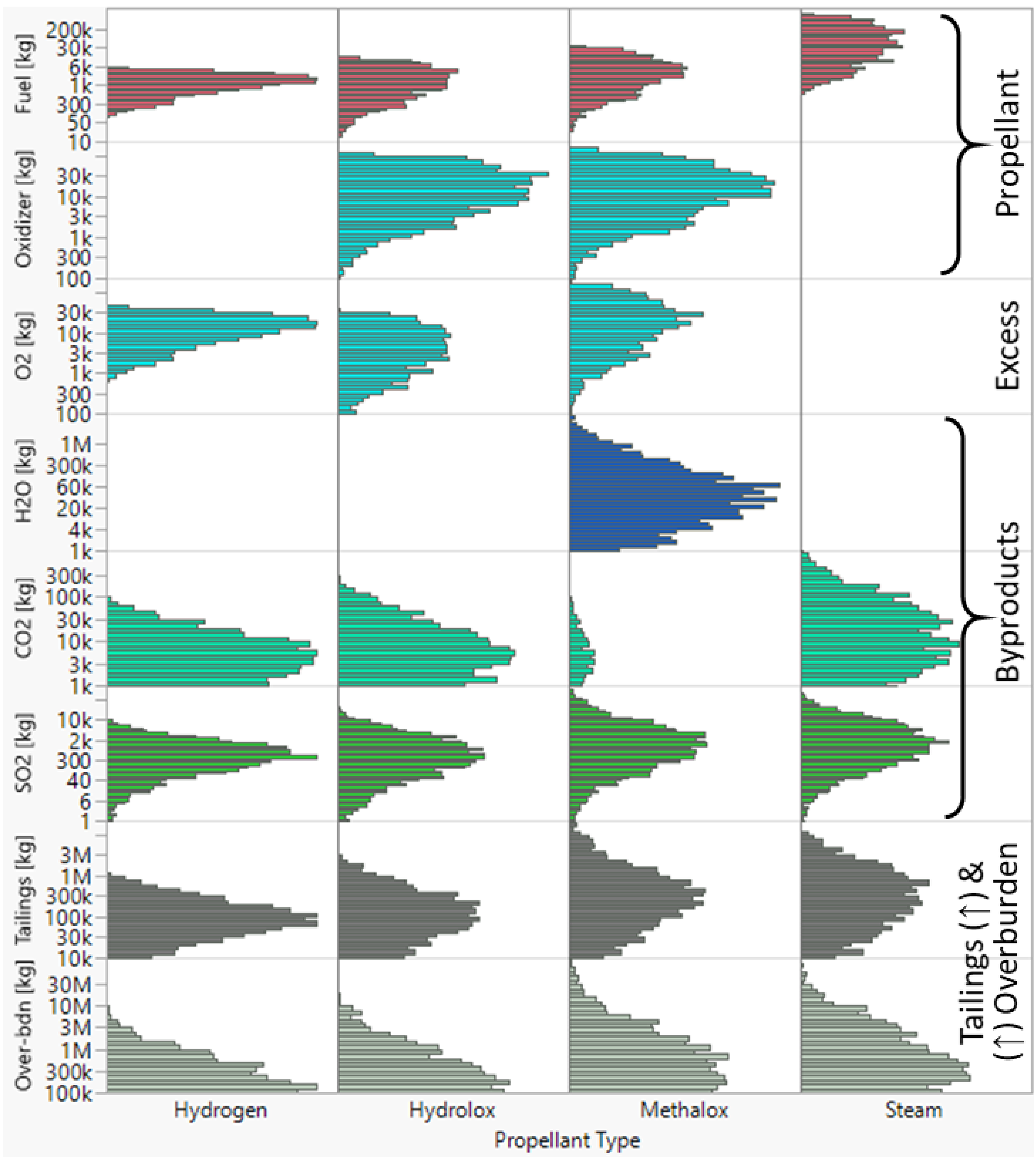


Figure C-11: Sored masses by substance (left) and categorization (right) as compared to the propellant masses produced in experiment 2

C.9 Thermal Management

The thermal module computes mass of thermal management system to keep SoS in a comfortable temperature rage. This means sizing both heating and cooling equipment. Note that the maximum irradiance and ambient temperature values computed in the rates module corresponding to the minimum heliocentric distance are expected to be input.

```
class Thermal __init__(self, Qc_dem_Wt, Qh_dem_Wt, flux_WPm2, T_amb_K,
        **kwargs):
```

C.9.1 Secondary Inputs

- `conc` - boolean switch between sizing solar thermal concentrators and heat lamps (default = False (IR Lamps); True (Concentrator))
- `cont__thermal` - Thermal management system mass contingency [%] (default = 0.3, or `'margin_frac'` if present)

Radiator Sizing (Secondary Inputs)

- `abs_rad` - absorptivity of radiators, in solar spectrum [frac] (default = 0.17, Zerlauts Z-93 White Paint ([466], [137] p. 695))
- `emis_rad` - emissivity of , in infrared spectrum [frac] (default = 0.92, Zerlauts Z-93 White Paint ([466], [137] p. 695))
- `emis_NEO` - emissivity of NEO [frac] (default = 0.9, for C-type Ryugu [193])
- `F_NEO_rad` - view factor of NEO irradiating radiators (default = 1/8) [137]
- `rho_rad_kgPm2` - Radiator area density [kg/m^2] (default = 8.80 kg/m^2 for 13.11 m Arterial Heat Pipe Radiators [467] p. 45) Note - assumed to include structural supports
- `eta_fin` - Heat pipe internal fin thermal conduction efficiency (default = .925 = 92.5% for 13.11 m Arterial Heat Pipe Radiators [467] p. 45)
- `mult_rad` - radiator subsystem mass adjustment factor for unsized components (default = 1.25 = +25%) - support structure, rotary joint & coolant

Infrared Lamp (Secondary Inputs)

- `irr_lamp_WPm` - Lamp radiative power provided per unit length [W/m] (default = 8000 W/m = 80 W/cm [468])
- `reflect_coat` - Proportion of light reflected by IR lamp back coating (default = 0.70 = 70%, Ceramic coating [468])
- `F_lamp` - View factor for IR lamp; proportion of light directly radiated towards target (default = 0.5, half of IR lamp coated [468])
- `L_lamp_m` - lamp heated length [m] (default = 0.38 m = 380 mm [469])
- `L_end_m` - lamp un-heated end length, per end [m] (default = 0.03 m = 3 mm, computed from [469])
- `d_fil_m` - tungsten filament diameter [m] (default = 0.02 m = 2 mm) Note - Coil approximated as solid rod
- `d_lamp_m` - outer diameter of quartz lamp casing [m] (default = 0.010 = 10 mm DIA [468])
- `thick_lamp_m` - thickness of quartz lamp casing [m] (default = 0.001 m, computed from 8x10 mm tube [470])
- `mult_lamp` - IR lamp subsystem mass adjustment factor for unsized components (default = 1.2 = +20%) - support brackets & wiring

Solar Thermal Concentrator Sizing (secondary inputs)

- `m_optics_kg` - mass of optical mirrors, lenses, & supports utilized [kg] (default = 500.64 kg, [20] p. 11)) #Telescoping tube assembly, includes large sapphire mirrors
- `eta_conc_th` - optical efficiency of light transmission [%] (default = 0.5 [20]) #Overall optical efficiency of 50% quoted

C.9.2 Key Formulae

```
#Infrared Lamp Sizing
Pe_lamp_We = Qh_dem_Wt * (F_lamp + (1 - F_lamp) / reflect_coat)
Qc_lamp_Wt = Qh_lamp_Wt - Qh_dem_Wt   #Inefficiency become cooling load
N_lamps = np.ceil(Qh_lamp_Wt / (irr_lamp_WPm * self.L_lamp_m))
m_lamp_kg = N_lamps * (rho_quartz_kgPm3 * ((L_lamp_m + 2 * L_end_m) *
      np.pi * ((d_lamp_m / 2 + thick_lamp_m) **2 - (d_lamp_m / 2) **2))
      + rho_W_kgPm3 * (L_lamp_m * np.pi * (d_fil_m / 2) **2))
```

```
#Radiator Sizing
flux_irr_WPm2 = (flux_WPm2 * self.abs_rad / 2 + boltzmann_WPm2K4 *
      self.emis_NEO * self.F_NEO_rad * self.T_amb_K ** 4 *
      self.abs_rad) #Irradiant flux from NEO
T_equl_K = flux_irr_WPm2 / (boltzmann_WPm2K4 * emis_rad)) ** (1/4)
rad_adj_WPm2 = (boltzmann_WPm2K4 * emis_rad * T_rad_K ** 4 -
      flux_irr_WPm2) * self.eta_fin
m_rad_kg =((Qc_dem_Wt + Qc_lamp_Wt) / rad_adj_WPm2)* rho_rad_kgPm2

#Aggregate System Sizing
m_kg  = (1 + cont_frac) * (m_rad_kg + m_lamp_kg + m_conc_kg)
P_We  = Pe_lamp_We  #Assumes IR Lamps Sized (conc = False)
Qc_Wt = Qc_lamp_Wt  #Assumes IR Lamps Sized (conc = False)
```

C.9.3 Verification of Module

Distributions for the thermal systems sized as part of experiment 2 are in Figure C-12 for reference. The NASA Life Support Baseline Values and Assumptions Document (BVAD) provides a range of expected cooling power mass penalties from $72\ \mathrm{kg/kW} \geq PMP_C \geq 190\ \mathrm{kg/kW}$ for radiator operation on the Lunar surface near the equator [108]. Note that Lunar surface values were used here due to having a large radiating body nearby. This range is shaded gray in Figure C-12 to the middle right. Note that the heating power mass penalty does not include cooling or electric requirements.

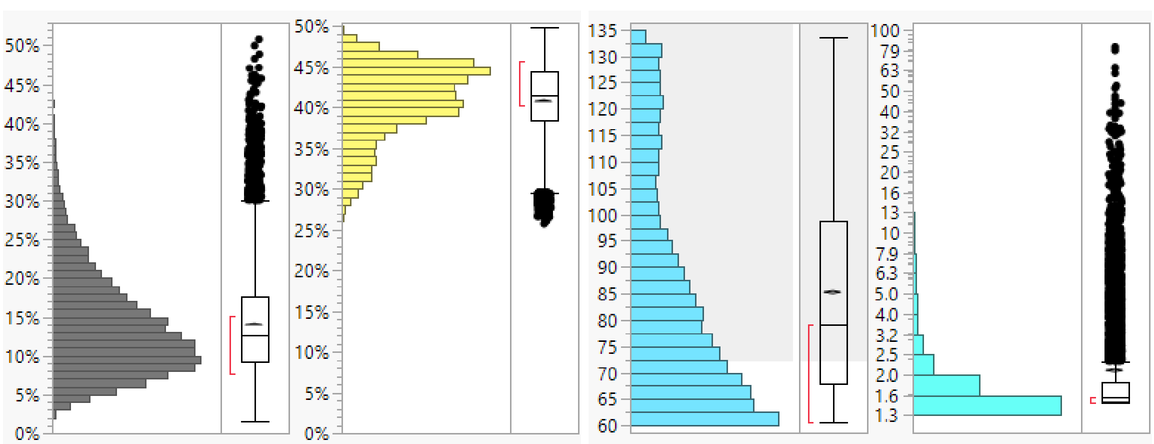


Figure C-12: Mass fraction (ζ_{Therm}) [%wt], energy use fraction (ξ_{Therm}) [%en], cooling (PMP_C) [kg/kW] and heating (PMP_H) [kg/kW] power mass penalty distributions for thermal system in experiment 2. Gray shading on cooling PMP is NASA BVAD values [108].

C.10 Power Management

The power class computes the mass of the power management system, which is assumed to be photovoltaics paired with secondary batteries. Note that the minimum irradiance and ambient temperature values computed in the rates module corresponding to the maximum heliocentric distance are expected to be input.

```
class Power __init__(self, P_dem_We, flux_WPm2, t_s, T_amb_K,
      period_NEO_h, **kwargs):
```

C.10.1 Secondary Inputs

- `cont__power` - Power management system mass contingency [%] (default = 0.3, or `'margin_frac'` if present [137])

Photovoltaic Array Sizing (Secondary Inputs)

- `eta_cell` - Cell demonstrated electrical efficiency (default = 29.8%, Quadruple junction GaAs, radiated with 1 MeV [471])
- `eta_light_path` - Overall electrical efficiency from power system, while solar panels illuminated (default = 0.80, [137] p. 643))
- `eclipse_frac` - Proportion of time plant is eclipsed in NEO shadow, or sunlight is otherwise too weak to be useable [%] (default = 0.5; half the time)
- `dark_opp_frac` - Proportion of time plant is operating during darker periods; uptime during subpar illumination [%] (default = 1; always online)
- `light_opp_frac` - Proportion of time plant is operating during sufficiently high solar illumination [%] (default = 1; always online)
- `sun_ang_max_deg` - Maximum angle between sun line and normal to panels during non-eclipsed configurations (default = 23.5 deg, GEO satellite, [137] p. 647)
- `abs_pv` - absorptivity of photovoltaic cell, in solar spectrum [frac] (default = 0.91, Quadruple junction GaAs, radiated with 1 MeV [471])
- `emis_pv` - emissivity of photovoltaic cell, in infrared spectrum [frac] (default = 0.85, for conformal coating on 'multijunction PV' [472])

- `emis_NEO` - emissivity of NEO, in infrared spectrum [frac] (default = 0.9, for C-type Ryugu [193])
- `F_NEO_pv` - view factor of NEO irradiating photovoltaics (default = 1/8) [137]
- `adj_therm_WPK` - electrical power output change with temperature (default = -0.3%, computed from QJ 4G32C data [471])
- `assy_mult` - Reduction in PV efficiency from assembly - includes lost area & coatings (default = 0.85, [137] p. 645)
- `degr_propPyr` - degradation per year (default = -2.7%/yr, for GaAS [137] p. 647; Note - `eta_cell` default includes 1 MeV radiation (~7% degr; 31.8% -> 29.7%) according to manufacturer, included to account for degradation due to transit time
- `rho_pv_kgPm2` - Solar cell area density (default = 2.8 kg/m^2 for GaAs Multijunction, [137] p. 648) Note - assumed to include structural supports

Lithium-Ion Secondary Batteries (Secondary Inputs)

- `E_bat_Wh` - energy per battery (default = 24.8 Wh 89280 J, Li-ion model MP XLR [192])
- `e_bat_WhPkg` - specific energy per battery (default = 180 Wh/kg = 648000 J/kg, Li-ion model MP XLR [192])
- `DoD_prop` - maximum depth of discharge for battery cells (default = 0.60, [137] p. 651))
- `eta_bat - efficientcy` of battery charging or discharging (default = 0.90, [137] p. 653)
- `mult_pv` - Photovoltaic subsystem mass adjustment factor for unsized components (default = 1.25 = +25%) - MPPT, rotary joint, wiring
- `mult_bat` - Battery subsystem mass adjustment factor for unsized components (default = 1.1 = +10%) - BMS, wiring

C.10.2 Key Formulae

```
#Photovoltaic Array Sizing
pv_WPm2 = flux_WPm2 * eta_cell * temp_mult * degr_mult * assy_mult *
      cos_mult
m_pv_kg = ((P_dem_We * dark_mult) / pv_WPm2) * rho_pv_kgPm2 * mult_pv
```

```
#Lithium Ion Secondary Battery Sizing
E_dem_J = P_dem_We * t_eclipse_s / (eta_bat**2 * DoD_prop)
m_bat_kg = ((N_bat * E_bat_Wh) / e_bat_WhPkg) * mult_bat

#Aggregate System Sizing
m_kg = (1 + cont_frac) * (m_pv_kg + m_bat_kg)
```

C.10.3 Verification of Module

Distributions for the power systems sized as part of experiment 2 are provided in Figure C-13. The NASA Life Support Baseline Values and Assumptions Document (BVAD) provides a range of expected electrical power mass penalties from $113\ \text{kg/kW} \geq PMP_P \geq 239\ \text{kg/kW}$ for operation in LEO for solar panels with secondary batteries [108]. This range is shaded gray in Figure C-13 to the right. Since this implicitly assumes a heliocentric distance of 1 AU and power systems were sized for $0.85\ \text{AU} \leq D_{max} \leq 1.45\ \text{AU}$ as per Table 6-2, the greater variance of the electrical power mass penalty observed is believed to be justified. Variance in the target NEO period of rotation is also believed to contribute to the variability observed, especially when the ratio of battery mass to solar mass is considered in Figure C-13 to the middle.

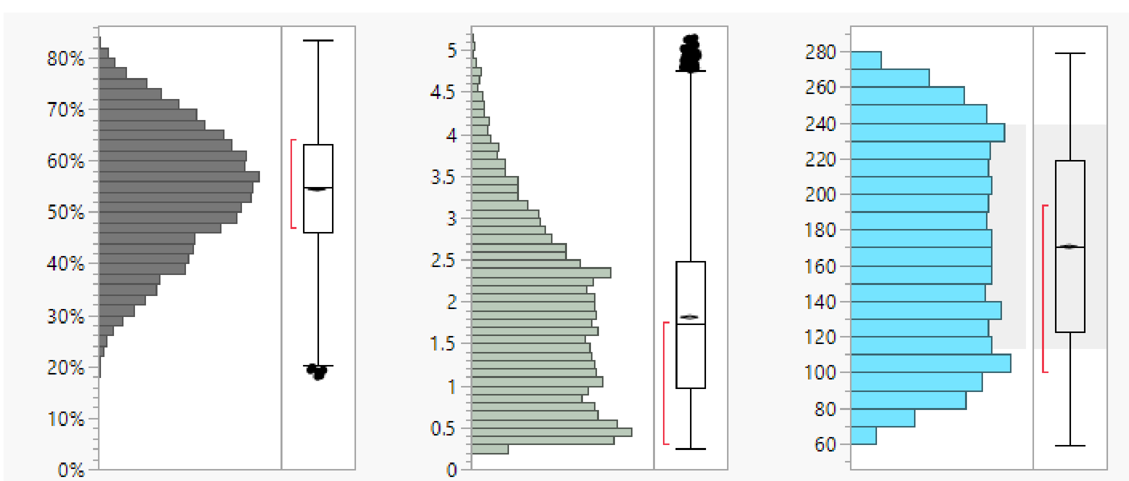


Figure C-13: Mass fraction (ζ_{POW}) [%wt], ratio of battery to solar panel mass [n.d.], and electrical power mass penalty (PMP_P) [kg/kW] distributions for power system in experiment 2. Gray shading on PMP is NASA BVAD values [108].

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