NIAC
NASA Innovative Advanced Concepts

Project RAMA

RECONSTITUTING ASTEROIDS INTO MECHANICAL AUTOMATA

MADE IN SPACE

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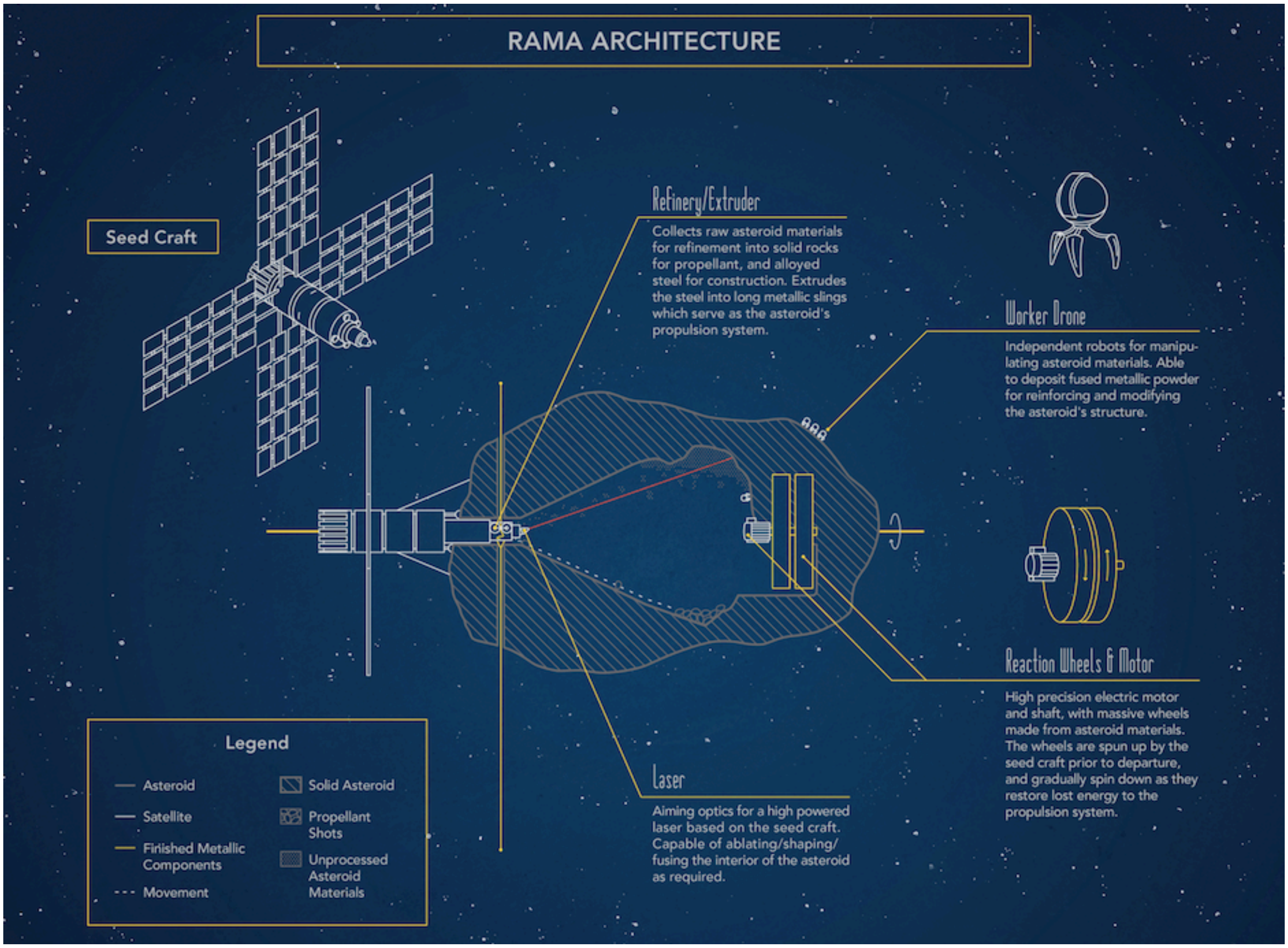
EXECUTIVE SUMMARY

“Those who control the spice control the universe.” – Frank Herbert, Dune

Many interesting ideas have been conceived for building space-based infrastructure in cislunar space. From O’Neill’s space colonies, to solar power satellite farms, and even prospecting retrieved near earth asteroids. In all the scenarios, one thing remained fixed - **the need for space resources** at the outpost. To satisfy this need, O’Neill suggested an electromagnetic railgun to deliver resources from the lunar surface, while NASA’s Asteroid Redirect Mission called for a solar electric tug to deliver asteroid materials from interplanetary space. **At Made In Space, we propose an entirely new concept.** One which is scalable, cost effective, and ensures that the abundant material wealth of the inner solar system becomes readily available to humankind in a nearly automated fashion. We propose the RAMA architecture, which turns asteroids into self-contained spacecraft capable of moving themselves back to cislunar space. The RAMA architecture is just as capable of transporting conventional sized asteroids on the 10m length scale as transporting asteroids 100m or larger, making it the most versatile asteroid retrieval architecture in terms of retrieved-mass capability.



Refinery/Extruder: Collects raw asteroid materials for refinement into solid rocks for propellant, and alloyed steel for construction. Extrudes the steel into long metallic slings which serve as the asteroid's propulsion system.

Worker Drone: Independent robots for manipulating asteroid materials. Able to deposit fused metallic powder for reinforcing and modifying the asteroid's structure.

Reaction Wheels & Motor: High precision electric motor and shaft, with massive wheels made from asteroid materials. The wheels are spun up by the seed craft prior to departure, and gradually spin down as they restore lost energy to the propulsion system.

Laser: Aiming optics for a high powered laser based on the seed craft. Capable of ablating/shaping/fusing the interior of the asteroid as required.

This report describes the results of the Phase I study funded by the NASA NIAC program for Made In Space to establish the concept feasibility of using space manufacturing to convert asteroids into autonomous, mechanical spacecraft. Project RAMA, *Reconstituting Asteroids into Mechanical Automata,* is designed to leverage the future advances of additive manufacturing (AM), in-situ resource utilization (ISRU) and in-situ manufacturing (ISM) to realize enormous efficiencies in repeated asteroid redirect missions. A team of engineers at Made In Space performed the study work with consultation from the asteroid mining industry, academia, and NASA.

Previous studies for asteroid retrieval have been constrained to studying only asteroids that are both large enough to be discovered, and small enough to be captured and transported using Earth-launched propulsion technology. Project RAMA is not forced into this constraint. The mission concept studied involved transporting a much larger ~50m asteroid to cislunar space. Demonstration of transport of a 50m-class asteroid has several groundbreaking advantages. First, the returned material is of an industrial, rather than just scientific, quantity (>10,000 tonnes vs ~10s of tonnes). Second, the “useless” material in the asteroid is gathered and expended as part of the asteroid’s propulsion system, allowing the returned asteroid to be considerably “purer” than a conventional asteroid retrieval mission. Third, the infrastructure used to convert and return the asteroid is reusable, and capable of continually returning asteroids to cislunar space.

The RAMA architecture, as described in this report, was shown to be cross cutting through the NASA technology roadmap as well as the future goals of the greater aerospace industry. During the course of the study it was found that the RAMA technology path aligns with over twelve NASA roadmap missions across seven NASA technology areas, and has the opportunity to substantially improve the affordability and scalability of both the Human Exploration and Operations Mission Directorate (HEOMD) and the Science Mission Directorate (SMD) stated goals.

The approach to studying this concept started with the development of *Rock Finder*, a rapid optimization tool for identifying suitable asteroids for utilization. In parallel to the *Rock Finder* development, a trade study was performed on various ISRU and ISM technologies. A technology roadmap was created to identify suitable technologies for turning asteroids into spacecraft. *Rock Finder* was then used to identify a single S-type asteroid, and a mission assessment was performed for a specific set of technologies, showing the feasibility of performing a RAMA style mission with the asteroid. The end results suggest that the RAMA architecture is a feasible way to automate a self-perpetuating suite of asteroid exploration, discovery, and utilization missions within a twenty to thirty year time horizon, demonstrating a maturation of the technology from TRL 1 to TRL 2.

PROJECT RAMA TEAM

Jason Dunn

Principle Investigator

Cofounder and CTO at Made In Space, Jason served the project as the PI. His role focused on the overall organization of the work plan and customer deliverables. Jason also managed the relationships with industry and academic experts. Jason was a main author of this report.

Max Fagin

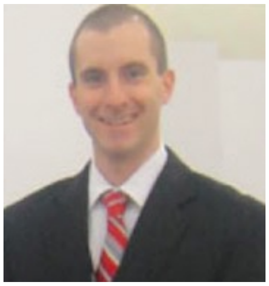
Lead Project Engineer

As the lead project engineer for the study, Max focused heavily the technical details of all work plan elements. The Rock Finder program was created by Max and was used to design the overall mission concept and trajectories. Much of the detailed mission concept is credited to Max. Max was a main author of this report.

Michael Snyder

Chief Engineer

Cofounder and Chief Engineer at Made In Space, Mike was in charge of overseeing the technical development efforts of the study. He was instrumental in determining the appropriate study path to be executed on, and directed the engineering focus.



Eric Joyce

Project Manager

As project manager of the RAMA study Eric managed the overall budget and schedule of the effort. His background expertise in space resources and mission planning was vital in directing the overall path of the study effort. Eric was active throughout the study maintaining alignment to study goals.

Supporting Roles

Phil Metzger, University of Central Florida – Phil brought his experience in ISRU and space resources to the RAMA study as a lead advisor to the work. The RAMA team consulted with Phil on mission concept design and resource mining options.

Andrew Rush, Made In Space, CEO – Andrew provided a role of ensuring the RAMA study maintained alignment to the overall Made In Space business focus. His contributions were seen through in depth reviews of work and connection to other Made In Space development programs.

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ACRONYM LIST

ABS	Acrylonitrile Butadiene Styrene
ADCS	Attitude Determination and Control System
AGI	Artificial General Intelligence
AM	Additive Manufacturing
AMF	Additive Manufacturing Facility
AREE	Automation Rover for Extreme Environments
ARM	Asteroid Redirect Mission
AU	Astronomical Unit (Earth-Sun Distance)
C&DH	Command and Data Handling
DMLS	Direct Metal Laser Sintering
DRM	Design Reference Mission
EBM	Electron Beam Welding
FBD	Functional Block Diagram
FSW	Friction Stir Welding
GMAT	General Mission Analysis Tool
GMAW	Gas Metal Arc Welding
GNC	Guidance Navigation and Control
GTAW	Gas Tungsten Arc Welding
IOT	Internet of Things
ISM	In-Situ Manufacturing
ISS	International Space Station
Isp	Specific Performance
ISRU	In-Situ Resource Utilization
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LBM	Laser Beam Welding
LD	Lunar Distance
LENS	Laser Engineered Net Shaping
LIDAR	Laser Imaging Detection And Ranging
LOX-H2	Liquid Oxygen + Liquid Hydrogen
MT	Metric Tonne
NEO	Near Earth Object
NEA	Near Earth Asteroid
NHATS	Near Earth Object Human Spaceflight Accessible Targets Study
NIAC	NASA Innovative Advanced Concepts
PMF	Propellant Mass Fraction
RAMA	Reconstituting Asteroids into Mechanical Automata
ROI	Return on Investment
RTG	Radioisotope Thermoelectric Generator
SBDB	Small Body Database
SEP	Solar Electric Propulsion
SOA	State of the Art
TCS	Thermal Control System
TRL	Technology Readiness Level
TTL	Transistor-Transistor Logic
ug	Microgravity
ΔV	Change in Velocity

1 INTRODUCTION AND BACKGROUND

The breakout into the High Frontier doesn't depend on our being so lucky as to find the asteroids… but it does depend on our working out the details of processing asteroidal materials to obtain from them pure metals, silicon, and oxygen. – Gerard O'Neill, "2081: A Hopeful View of the Human Future," 1981

1.1 PROBLEM AND MOTIVATION

Humanity has evolved on the largest solid body in our solar system, and transporting anything into space is an energy and cost intensive process. So intensive, that if all the materials we have ever launched into space were collected and compressed into a single solid body, it would occupy a region no bigger than a tennis court [28]. But space already contains billions of objects of this mass or greater: The asteroids.

It has long been understood that harnessing the mass of the asteroids and using it to manufacture equipment outside of Earth's gravity well would be an enabler of the space frontier. The exploitation of asteroid resources has the potential to transform our activities in space from one of Earth dependence to one of Earth independence. Fuel depots in cislunar space, large-scale space manufacturing facilities, future space stations (Figure 1-1), and mega-scale space structures would bankrupt the world if the mass to build them needed to be launched from Earth, but the cost of these projects suddenly become feasible with an available supply of asteroid resources.

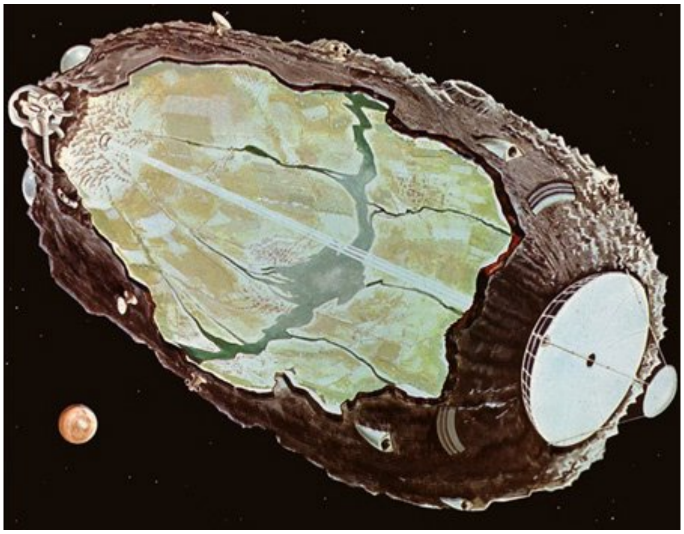


Figure 1-1: An early hollowed out asteroid concept as envisioned in the 1965 book "Beyond Tomorrow: The Next 50 Years in Space" by Dandrige Cole and Roy Scarfo.

In addition to enabling space based industries, asteroid resources present advantages to industries here on Earth. Global resource consumption is increasing at a rate proportional to both population growth and the rate at which existing populations increase their demand for resources [17] [18]. Exponentially accelerating technologies, backed by Moore's Law, are bringing about incredible benefit to humanity, while requiring more resources and energy to be consumed to create these new devices. Six separate studies have estimated that within two decades there will be a global demand for over forty-five trillion sensors [20]. This is formally known as the "Internet of Things" (IOT). The question then to ask is, "where does the energy and resources come from to create these devices?"

With current exploration and extraction methods, there are not enough raw materials present on Earth for the world's current population to experience the quality of life of the modern developed world [18]. This shortage clearly poses a problem for the upcoming decades not just for the entire population to rise to current living standards, but also to meet the growing technological needs on the horizon. The cost threshold may continue to be met as it has been in the past by further advances in terrestrial resource extraction and recycling; but such advances may not be necessary, given that the same resources are found in abundance in the asteroids. And regardless of what technological advances are made in terrestrial technologies, there are likely to be externalities to the land, environment and local populations.

Asteroid mining is guaranteed to be free of these costs, making asteroid resources "greener" than terrestrial resources ever could be, regardless of future innovations.

For now, the cost to mine these asteroids is far more expensive than the cost of extracting equivalent resources from Earth. But that will not always be true. In the next few decades, the convergences of several exponentially accelerating technologies are expected to dramatically reduce costs for space resource mining endeavors. Logically there will be a tipping point when it will become economically feasible to switch to an off-world resource extraction and mining paradigm.

These observations are by no means novel or original [28]. But they have gained credence in recent years as the aerospace community witnessed the birth and growth of several space resource exploration and exploitation initiatives to capitalize on the opportunity. NASA's path finding efforts in programs such as the Asteroid Redirect Mission (ARM) have shown national interest and support, while commercial firms such as Planetary Resources, Inc. and Deep Space Industries, Inc. have demonstrated that space resources represent a financeable endeavor. Internationally, the government of Luxembourg has demonstrated this fact with an investment of over $200 million in strategic space resource developments, and domestically, the United States demonstrated its commitment with the SPACE act of 2015, recognizing property rights to resources mined in space.

The value of mining asteroid resources is clear; but enabling such a mission requires solving many complex challenges [21]. Furthermore, from industry research and technology roadmaps the authors of this report believe that all but one of these challenges is being addressed by current asteroid exploitation initiatives or from other crosscutting industries. The focus of this NIAC Phase I study is to solve the last challenge on this list.

- **Remotely mining asteroids without the need for humans –** Advances in artificial intelligence and robotics are on a steadily increasing curve of capability while on a decreasing curve of cost, largely driven by advances in microprocessors.
- **Data collection and asteroid detection –** Improved sensors, Big Data computation capabilities, and improvements in microprocessors will make for finding more near-Earth objects far more efficiently than today.
- **Launch and propulsion –** Advances in both chemical propulsion technologies, reusability of rockets, and new in-space propulsion technologies will make transportation to and from mining outposts fit within the economic needs of an off-world mining infrastructure.
- **Design –** Generative design algorithms are allowing for new mission designs to be created in an organic evolvable fashion. This in turn creates a more efficient design of both spacecraft and mining infrastructure.
- **Miniaturization –** The rapid miniaturization of spacecraft technology will enable mining infrastructure to be optimized for both low cost launch and scalable exploration. This will help enable an increase in scouting missions.
- **Transportation of asteroid resources –** While there have been some concepts for how to transport small samples of asteroid materials from its orbital location to a mining/manufacturing outpost, there currently exists no method that enables the continuous, automated delivery of entire asteroids from interplanetary space to a single mining/manufacturing location of interest. **This *core-unsolved problem* is the focus of the Project RAMA Phase I study.**

1.2 A VISION OF SPACE DEVELOPMENT

Since the beginning of the space race, the space industry has operated under a set of assumptions:

(1) All space missions start at the bottom of Earth's gravity well, and are delivered to space on launch vehicles employing chemical propulsion.

(2) Space missions are controlled from Earth, and cannot function without regular communication with Earth.

(3) "Space Industry" means using space to produce data, not physical products (i.e. telecommunications, remote sensing, Earth observation).

The later assumption is the one that will be challenged in the near future. Made In Space believes that space will become a useful place to produce physical goods, to enable future jobs, and to expand our global economy. The transport of materials (not just data) between Earth and space will open up a new set of industries, in which space manufacturing facilities become a cornerstone of the expanded space economy. The space environment will be leveraged in the production of equipment that can only be produced in space. Microgravity (and partial artificial gravity) will be used to precisely control the manufacturing of products made from exotic materials. Manufacturing processes that on Earth rely on the costly use of inert gasses will be moved to space, where an abundant supply of vacuum can provide the same effect. The heat dumped into Earth's oceans and atmosphere will instead be radiated out to the blackbody of the universe. With growing concern and understanding of Earth's changing climate, it's not hard to imagine a point where large industrial operations are moved off-planet to avoid the chance of environmental damage.

The challenge of the space industry lies in the preparation of meeting these future needs. Transportation companies providing both up-mass and down-mass must be ready to handle the demand of transporting both people and equipment to and from space. Advanced space manufacturing capabilities must be available for the construction of both large scale space habitats as well as small scale precision parts. Life support systems must advance to fully regenerative status to reduce the need for Earth re-supply. Energy production and storage techniques must be ready to provide megawatt class power. And finally, the resources of the solar system must be tapped to provide easy routes for this growth to take place.

Fortunately, these challenges can be solved by the clever adaption of technologies under development on Earth right now. For many decades, any industry or product that is enabled by the exponential growth of information technology in turn falls onto an exponential price/performance level of growth. This acceleration is more and more evident in recent years. Miniaturized computers, smart phones, wearable devices, consumer drones, and even satellites are now "information technologies." The CubeSat, which was once an educational exercise in spacecraft systems engineering, now packs so much capability that the aerospace industry is moving away from massive satellites towards constellations of small, resilient, highly advanced smallsats. These trends are nowhere near their theoretical limit, and are expected to continue to accelerate in capability and performance.

This steady advancement affirms the positive view that the industrialization of space will commence in the next few decades. Enabled by "big data" computation capabilities and artificial intelligence algorithms trained by machine learning, the space robotic systems of the near future will be a far cry from even the state of the art robotics in space today. For the early history of robotics pattern recognition was too undeveloped to make robots anything more than a "teach-and-repeat" level of automation. A very handy tool on the assembly line, but not capable of handling something as complex as a space mission without regular human supervision from Earth. Recent advancements in computation and pattern recognition are changing this. Robotics now and in the near future will be capable of performing the complex decision making tasks required for space exploration. And in an environment where the risk to human life is so high, the robotic construction worker will be gladly welcomed. With these highly capable robotics, and access to the vast amount of space resources, a new era in space exploration will be unlocked.

1.3 THE RAMA SOLUTION

Made In Space developed RAMA to solve the problem of transporting large supplies of asteroid resources from their natural orbits to orbits of greater use in cislunar space. RAMA is a revolutionary, mass-minimalist approach to explore and exploit space resources. The concept is based on a “Seed Craft”; a spacecraft which contains technically sophisticated ISRU, Additive Manufacturing and robotic capabilities. The Seed Craft uses these capabilities to convert the available materials of an asteroids into spacecraft subsystems including propulsion, energy storage and guidance systems. The asteroid (now a spacecraft in its own right) is able to autonomously carry out a basic mission; such as relocation for easier future rendezvous, or to divert to a more useful location empty space. Meanwhile, the Seed Craft which initiated the transformation is free to plot a course to the next asteroid, repeating the RAMA process indefinitely.

Designing RAMA and the Seed Craft is a project of advanced automation. To accomplish a task as difficult as converting an asteroid into a spacecraft, the Seed Craft must be outfitted with sophisticated robotic manufacturing and material processing technologies. Such technologies do not yet exist, but we anticipate ten to twenty years from now they will be developed to a technology readiness level high enough for the initial RAMA missions. With computation capabilities that rival todays super computers, the Seed Craft would be able to plan an entire mission on its own, adapting and building new equipment to accommodate the unique conditions it encounters on each asteroid.

We can be hopeful for the future of these technologies because many are currently in active development in other industries, with large growth potential here on Earth. Alphabet, the parent company of Google, has a fleet of self-driving automobiles on the roads of Silicon Valley where Made In Space is head quartered. These vehicles adopt low cost LIDAR and radar sensors married with sophisticated feedback, machine learning, and other software tools to provide a level of driverless autonomy that meets the high standards of our nation’s roadways. Made In Space is currently working on the space manufacturing technologies that, among other capabilities, will enable the RAMA mission. Vacuum based additive manufacturing of polymers, metals, and composites in microgravity; large-scale structure manufacturing/assembly in space, and advanced robotics are all under currently funded programs at Made In Space.

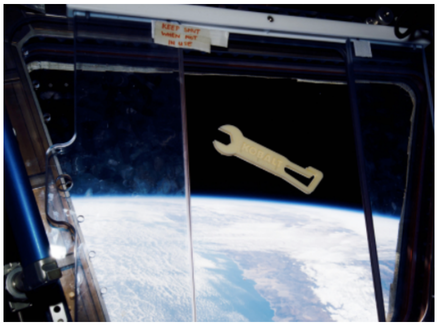
RAMA Benefits

Compared to the state-of-the-art (SOA) Asteroid Redirect Mission architecture, **RAMA simply does more for less** [1]**.** Because RAMA makes use of materials found at the asteroid for mass intensive tasks (like providing reaction mass for the propulsion systems), a greater mass can be returned for equivalent mass launched. This is even more true if the RAMA Seed Craft can redirect multiple asteroids in a single mission, either by using the asteroid’s propulsive capabilities to redirect itself towards another target before returning, or using the asteroid’s resources to replenish the Seed Craft’s propellant reserves. The asteroid-spacecraft itself also has several advantages over transporting resources with conventional spacecraft. An asteroid spacecraft can be 100% radiation hardened due to the abundance of shield material, and its interior can be completely shielded from micrometeorite debris, making it ideal for long-term missions on the order of 5-50 years [12]. Due to the composition of these ISRU-derived (largely mechanical) systems, the "useless" materials on the asteroid (that would be separated and disposed of once the asteroid had returned to cislunar space) is put to good use in the RAMA concept as structural support and propellant reaction mass.

Taken to the extreme, the RAMA architecture enables a continuous train of resources to be redirected from interplanetary to cislunar space: A train of mechanically driven, asteroid spacecraft, "mine carts," stretching from the depths of the asteroid belt to within 1 Lunar Distance (LD) of the Earth-Moon system. A symphony of endless revolving resources working in concert that, once in place, humans could hitch aboard and use as "free rides" to interplanetary space and back. Over time, such a system could convert these rudimentary spacecraft into sophisticated vehicles fit for human habitation; or fit them with sensors as research platforms to map other asteroids. Ultimately RAMA will create a system that will give humanity access to safer, faster and cheaper options for accessing the wealth of resources in our solar system.

1.4 RELATED WORK AT MADE IN SPACE

Made In Space brings forth a legacy of space manufacturing expertise to the study of the RAMA concept. The pioneering efforts of 3D printing in microgravity, beginning in 2011 on parabolic research flights and later on the International Space Station in 2014 form the foundation for the working knowledge for approaching the RAMA problem set. All the work at Made In Space is focused on a roadmap of enabling more and more to be manufactured in space, so that less and less must be launched from Earth over time. While the concept of Project RAMA exists on the far end of the Made In Space roadmap, there are many programs currently in progress with near term horizons that are enabling to the RAMA vision. The following is a description of three active programs at Made In Space; each playing a critical near term step in enabling the future RAMA mission technology needs.

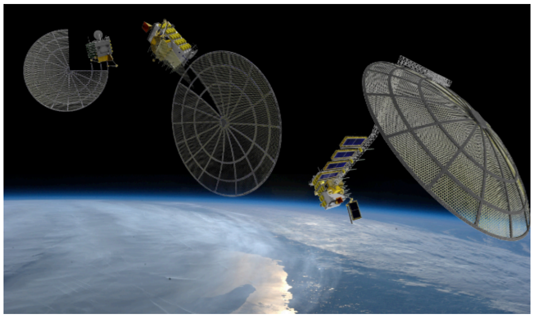


3D printed wrench made by AMF on ISS

Microgravity Additive Manufacturing: The Additive Manufacturing Facility (AMF) onboard the ISS is owned and operated by Made In Space offering in-space manufacturing as a service to both NASA and other organizations around the world. The techniques developed by Made In Space to enable AM to work in microgravity are key technologies needed to enable the Seed Craft to convert asteroids into spacecraft. The microgravity AM technology can produce parts in a variety of materials from advanced thermopolymers to ceramics and metals.

Space Resource Manufacturing: Under development at Made In Space are several methods for additively manufacturing products from local resources. This technology is capable of working on planetary surfaces, such as the Moon and Mars, but would be perfectly applicable to an asteroid manufacturing mission. Pictured here is a gear produced using JSC-1A lunar regolith simulant as a feedstock material along with an additive manufacturing technique. The Seed Craft may create gears and other mechanical parts in a similar manner.

Gear made by Made In Space from JSC-1A



Archinaut program for robotic space mfg.

Large Scale Space Manufacturing and Assembly: Made In Space and NASA are operating together on a Public/Private Partnership through the Archinaut Program. Archinaut is a platform of technologies that make possible the manufacturing and assembly of very large structure in the space environment. The near term goals of Archinaut are to construct large spacecraft elements using materials launched from Earth, but the same methods may one day be used with the Seed Craft to create large structures out of asteroid materials in-situ.

1.5 ASTEROIDS: WHAT AND WHERE?

Any discussion of asteroid resources must begin with an understanding of the asteroid's composition, structure, and distribution throughout the solar system. The study of asteroids is a highly specialized and continuously evolving field, but a general introduction is provided here, based largely on information provided in [29].

Asteroid Distribution: Collectively, the asteroids represent a total of $3{\cdot}10^{21}$ kg of material, equivalent to ~5% the mass of the Moon, or a single body ~1400 km across. The majority of this mass is contained within the ~900 km dwarf planet Ceres, and most of the remaining mass is distributed in the main belt between Mars and Jupiter.

It is nearly impossible to state any universal rule about asteroids, as their sheer number ensures that there will be exceptions to every rule. For example, even though the majority of asteroids are located in the main belt, a large number exist in Earth crossing orbits that make them much more accessible (and easier to detect) than the main belt population. These asteroids are collectively referred to as Near Earth Objects (NEOs) and are defined as any asteroid with a minimum orbital radius of <1.3 AU. Given their proximity to Earth, NEOs are the most heavily studied, and will likely be the first asteroids to be tapped for their resources.

Due to a continuous process of collision and accretion that began when our solar system formed (and which continues today), asteroid sizes have been smoothed out to follow a predictable power law. This trend is depicted in Figure 1-2. In general, an asteroid of any size is ~100 times more prevalent than an asteroid 10 times its own size. So if a given region of space can be seen to be populated by 100 asteroids with diameters >10km, it is reasonable to assume that there are ~1,000,000 undetected asteroids in the same region with diameters >100m. No comprehensive telescopic survey has yet been conducted with the ability to detect asteroids <100m in diameter, and our knowledge of asteroids of this size is limited to the small population that has been detected when one makes a fortuitous close pass of Earth.

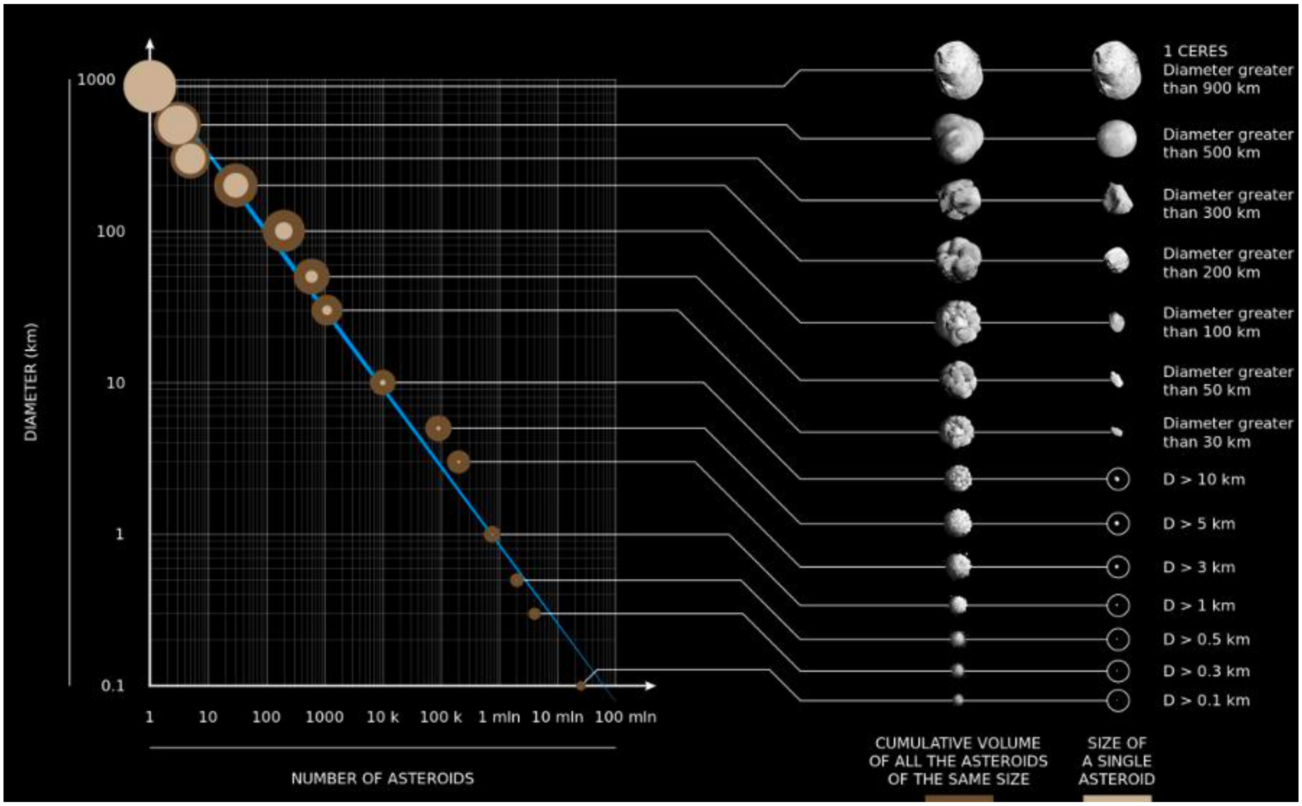


Figure 1-2: Asteroid Size Distributions (Source: Marco Colombo, Density Design Research Lab)

Composition: Asteroids formed from the same circumstellar cloud of gas and dust as the inner planets, so their bulk composition is generally similar to Earth. However, Earth's larger mass and gravity has allowed its interior to remain hot and geologically active, concentrating various materials through processes that never took place on the asteroids. Asteroids thus tend to be more homogeneous and undifferentiated than Earth. While Earth's surface and interior show high differentiation and can be divided into layers and geological zones, a sample from one part of an asteroid is likely to be similar to every other part of the same asteroid.

This lack of differentiation offers both advantages and disadvantages for resource utilization. One advantage is that it makes characterization of an asteroid's composition considerably easier. Unlike Earth, an asteroid's composition is not a strong function of location, and any materials found on an asteroid's surface are likely be present throughout the asteroid's interior. A lack of differentiation also means that valuable materials that are locked up in inaccessible regions on Earth are within easy reach on asteroids. Metals like iridium, which on Earth are mostly dissolved deep in our iron core, are distributed uniformly throughout an asteroid. Rare platinum group metals can only be found on Earth in locations where geologic process have brought them near the surface. But on asteroids, they are likely distributed throughout the body, and can be naturally separated while mining for other minerals.

The disadvantage to this lack of differentiation is that much larger volumes of asteroid materials must be processed to yield the same quantity of resources. Mining on Earth is frequently a process of following veins where minerals are present in higher quantities than in the surrounding deposits; By contrast, mining on asteroids is likely to focus more on moving and processing large volumes of a uniformly low grade ore.

Structure: Medium sized asteroids (1-100 km in diameter) have sufficient gravity to adhere small rocks and regolith to their surface, but insufficient gravity to develop the internal pressure or heat required to melt or separate their interiors (Figure 1-3). Asteroids in this size range tend to resemble loose packed agglomerations with a porous structure. Mining material from these asteroids will require comparatively little breaking or mechanical processing, as an assortment of materials in a range of sizes is already available. By contrast, small asteroids <100m in diameter are more likely to be a single continuous body, as their surface gravity is too weak to hold on to anything loosely packed. The continuous nature of small asteroids is also evident from studies of their rotation rate. Small asteroids are regularly observed to be rotating rapidly enough that centrifugal force at their surface exceeds that of their gravity, implying that the body must have some internal cohesion in order to remain intact [5]. This can be expressed by the criteria where the period is small enough for centrifugal force to exceed gravitational acceleration seen in Equation 1.

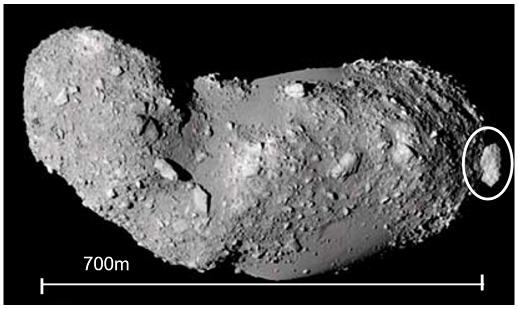


Figure 1-3: Asteroid Itokawa, imaged from the Hayabusa spacecraft. Note the loose packed structure composed of multiple smaller solid bodies.

$$\omega^2 r > \frac{GM}{r^2}$$

Equation 1: Criterion for an asteroid being unable to remain gravitationally bound

Which, in terms of the asteroids diameter d, Mass M, and revolution period T can be expressed as Equation 2.

$$T < \sqrt{\frac{\pi d^3}{2GM}}$$

Equation 2: Criterion, which if met, suggests the asteroid is a single solid mass rather than a gravitationally bound collection of smaller masses

Any asteroid which is observed to meet this criterion is known to have significant internal cohesion. Knowledge of the period of revolution can be obtained by repeated observations of the asteroid and detecting cycles in its apparent magnitude, but knowledge of the asteroids diameter and mass cannot be known accurately without up close observations from a spacecraft. This method should thus be used with caution.

The mining techniques deployed on these small monolithic asteroid will be very different than those deployed on a medium asteroid, requiring the ability to break down large chunks before processing. This can be an advantage, as the monolithic structure can negate the need for support or reinforcement to brace the asteroid against acceleration.

Albedo/Magnitude: Ground based observations are not able to resolve asteroids as anything other than point sources except during very close passes of Earth. The only way to infer an asteroid's size from ground observations is by measuring the amount of light it reflects. Like with stars, this measurement is quantified with a photometric magnitude system, where a lower magnitude corresponds to a brighter source, and each step of -1 magnitude equates to a factor of 2.5 increases in the intensity of the source.

An asteroid's apparent magnitude is not a simple function of its distance from the observer, but also of its phase angle (the angle between the sun, the asteroid and the Earth) and its albedo (the tendency of its surface to reflect light), as shown in Figure 1-4. Different asteroid types will have different surface coatings, which preferentially scatter light in different directions, further complicating the estimation of an asteroid's size from its magnitude. Asteroids tend to have dark, non-reflective surfaces with albedo values of .04-.20, making them as dark as asphalt.

By convention, the absolute magnitude of an asteroid is defined as its apparent magnitude when it is 1 AU from the Earth and from the Sun. A typical 50m asteroid may have an absolute magnitude of ~26, illustrating the difficulty in detecting these small objects except when they are very close to Earth (typical limits on telescopes dedicated to asteroid surveys are 21-24, meaning a 50m asteroid in a 1AU orbit may not be detected until it is within 0.1-0.3 AU of Earth. This further highlights the distinction between proven and unproven resources in asteroid mining. Estimates of potential resources must be informed by the understanding that all asteroid surveys are partial surveys only.

Tracking/Naming: Because the vast majority of asteroids are too dim to be detected except when they are close to Earth or at a favorable phase angle, asteroids can go several years after detection without being observed again. Asteroids in orbits with periods similar to Earth's will only make close passes of Earth every few decades, complicating the process of re-acquiring them once they have been lost. The convention for discovery and identification of asteroids requires observing them on multiple passes (typically 4-5) before their orbit is sufficiently well characterized to not be lost again. Once an asteroid has met this threshold, it is assigned a unique discovery number (e.g. 2350751). Until then, each asteroid is referred to by its discovery year and a temporary letter code (e.g. 2002 AW). The vast majority (>90%) of asteroids have yet to be observed a sufficient number of times for a precise orbital fix, so asteroids are most commonly referred to by the temporary discovery year and letter code.

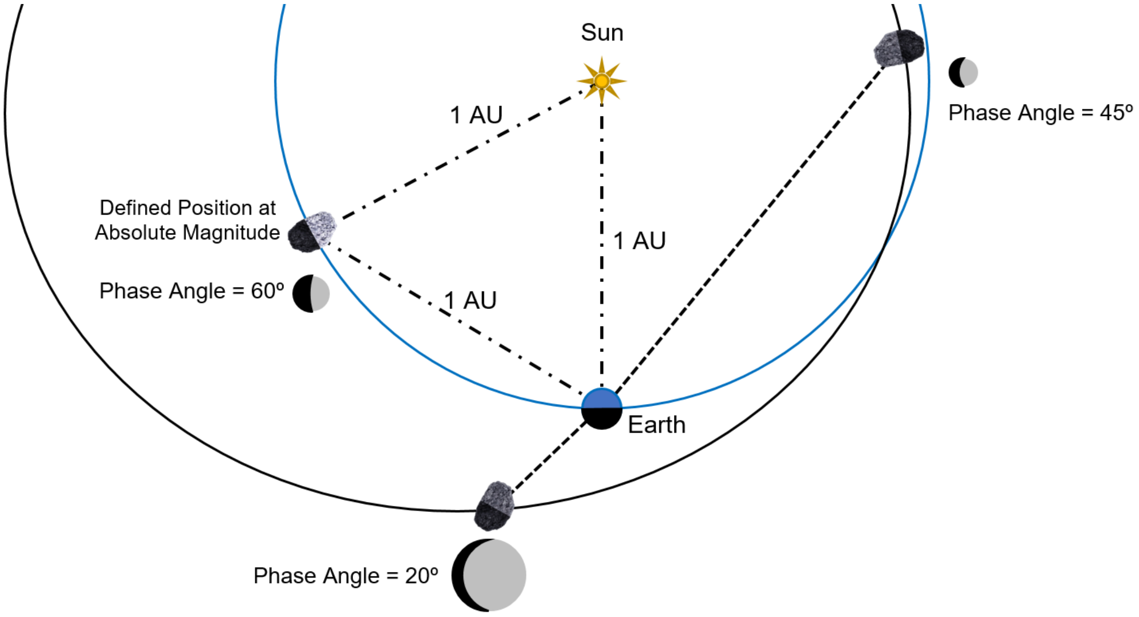


Figure 1-4: Factors contributing to an asteroid's apparent magnitude. An asteroid just outside of Earth's orbit and at low phase angle will be almost fully illuminated, and physically closer, making it much easier to detect than one which is inside Earth's orbit and far away. The absolute magnitude of an asteroid is defined as the apparent magnitude it would present if it were located 1 AU from both the Earth and Sun. Note how the asteroid may never actually occupy this position.

Physical Properties: Once an asteroid's absolute magnitude H has been measured, and an estimate of its albedo α has been made (or assumed) an estimate of the asteroid's diameter can be derived from the empirical relationship seen in Equation 3.

$$\mathrm{d} = 1.329 \cdot 10^{6}\ \alpha^{-1/2} 10^{-\mathrm{H}/5}\ \text{meters}$$

Equation 3: Asteroid diameter as a function of measured albedo

Very little additional information can be obtained beyond this from telescopic observations alone. If repeated observations can be taken frequently enough, it is possible to measure the small changes in brightness that occur as the asteroid rotates, thus providing a measurement of the asteroid's spin rate and approximate shape. If the asteroid can be imaged in multiple color filters, an estimate of its composition and type can be made (though high-resolution spectral data is still required to confirm). Observations beyond position and magnitude are not commonly collected due to telescope time and cost constraints, so the sum total of all "known" information about an asteroid is often limited to its approximate orbit, and a very rough estimates of its size. Nothing can be known about its shape, mass, density or composition without additional observations. Next to diameter, the most important property of an asteroid is arguably its mass, which is impossible to measure from the ground. Until the asteroid is visited by a spacecraft, details like its mass can only be guessed at.

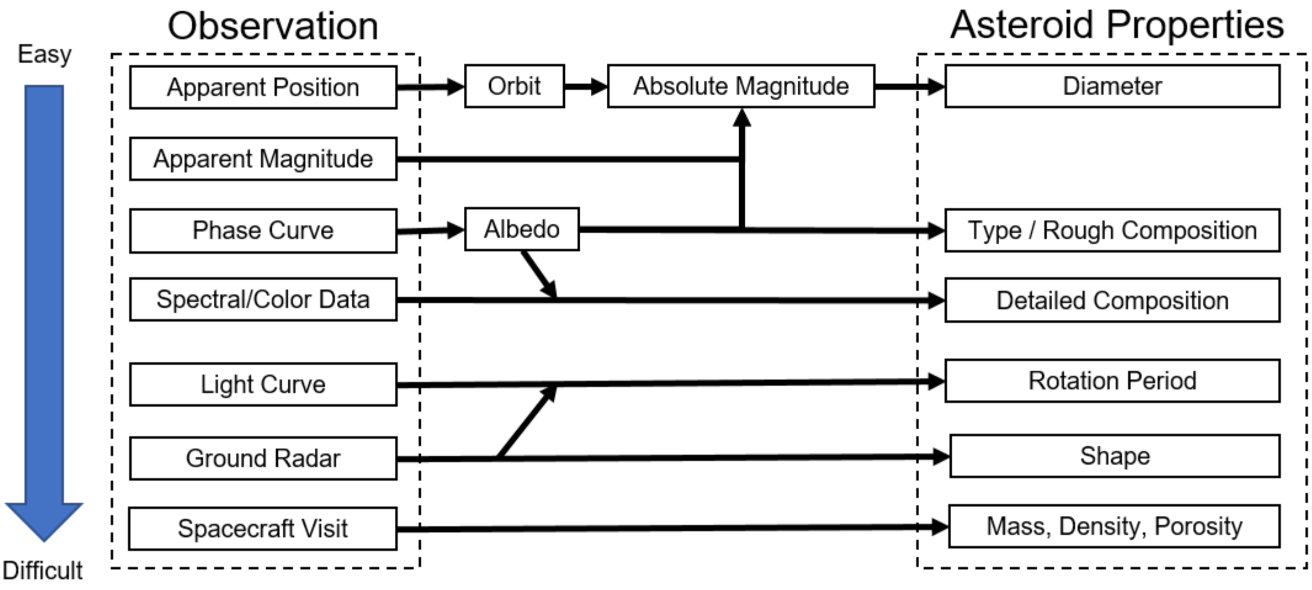


Figure 1-5: Asteroid Observations and Properties. The combination of observations that are required to derive reliable measurements of an asteroid's properties.

Asteroid Types: As shown in Figure 1-5, an estimate of an asteroid's type and composition requires multiple measurements in multiple color bands, or detailed spectral data. No common database of asteroid spectra exists at the moment, but a rough taxonomy of asteroids has still been developed by matching available spectral data to identified meteorites found here on Earth. The two most common types are described below and shown in Table 1-1:

> C-cadre: More common in the main belt, less common near Earth orbit. Characterized by a darker albedo, lower density, and a higher prevalence of organic compounds, water-ice and other volatiles.
>
> S-cadre: The most common near Earth object type, but less common in the main belt. Characterized by a high albedo, and a stony/metallic composition with very little water-ice or volatiles.

The details of an asteroid's composition can cover a wide range, even within a given type, and there is a large amount of overlap/ambiguity between types. The general properties are shown in Table 1-1: Properties of various general asteroid types, and their relative abundances throughout the inner solar system are shown in Figure 1-6.

Table 1-1: Properties of various general asteroid types

Class	C cadre	S cadre
Sub-types	B, C, D, F, G, P	K, M, S
Surface	Dark, fine regolith coating	Bright, exposed surface
Interior	Loosely packed	Contiguous, Dense
High Prevalence	Volatiles, Water, Organics	Silicates, Metals

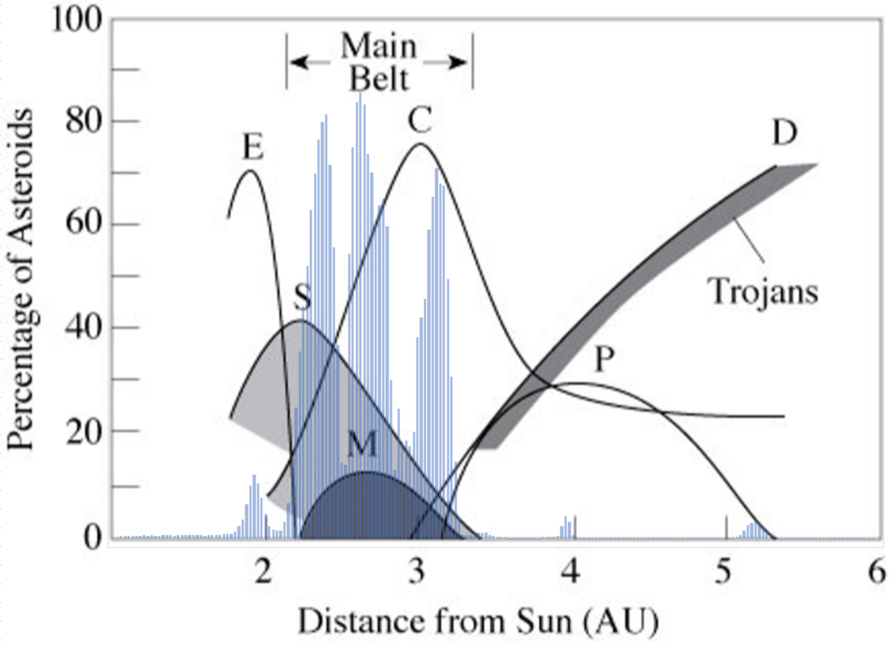


Figure 1-6: Distribution of Asteroid Types as a Function of the Distance from the Sun. The percentage of the population represented by various types is shown in grey, while the total number density in each orbit is shown in blue. The gaps are the so called "Kirkwood Gaps", caused by orbital resonances with Jupiter and Saturn. At these distances, an asteroid's orbit is not stable, and will be quickly perturbed to a lower or higher orbit. Adapted from K.R. Lang 2010, number density data from JPL.

2 RAMA ARCHITECTURE CONCEPT

2.1 THE ASTEROID SPACECRAFT

The purpose of the RAMA spacecraft is to leverage a small amount of mass and equipment delivered to the asteroid by a Seed Craft, and use it to return a larger mass of asteroid raw materials to cislunar space. To accomplish this, the RAMA craft requires all the functions of a conventional interplanetary spacecraft, subject to the constraints that they be 1) Manufactured from materials available on the asteroid, 2) Manufactured on/by equipment available on the Seed Craft. The specific solution will depend on the asteroid, but in general, the RAMA craft must have the capabilities shown in Figure 2-1.

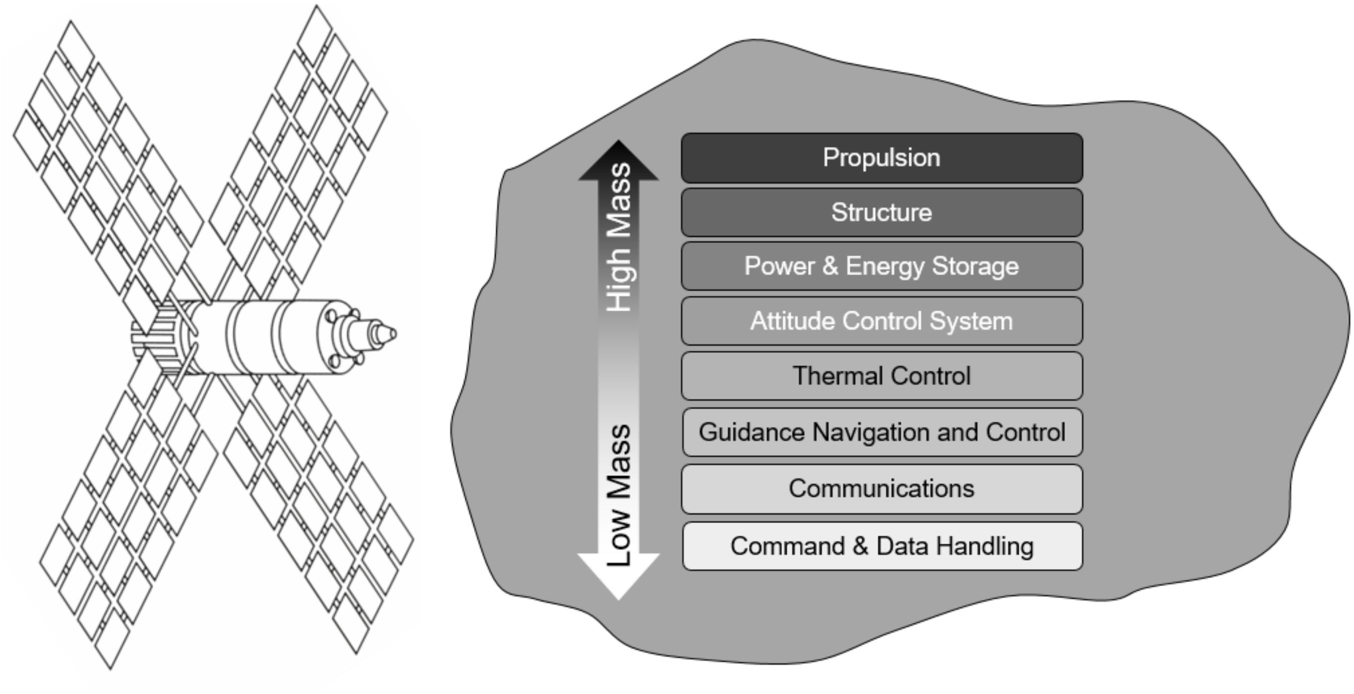
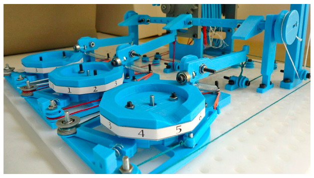


Figure 2-1: The Asteroid Spacecraft Mass Requirements. The required capabilities of the RAMA craft, arranged in approximate order of their mass requirements.

2.2 MECHANICAL SYSTEMS CAPABILITIES & LIMITS

2.2.1 CREATING SPACECRAFT FROM MECHANICAL SYSTEMS

Mechanical and analog devices have been in existence for centuries. Examples of mechanical computing devices date back to 200 BC and were used as navigational instruments in the early days of spaceflight before being superseded by electrical computers. Figure 2-2 outlines eight different mechanical machine examples. The combination of these examples establishes a level of feasibility for constructing spacecraft from mechanical systems. Additionally, research and development in this field has led to analog based 3D printers that require no power or electronics to manufacture a pre-designed object.

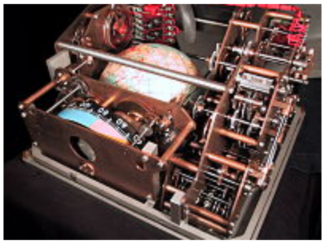


(A)

3D Printed Mechanical Computers - There are multiple examples of analog computing devices performing orbit calculations.

(B)

Theo Jansen's Strandbeest - Demonstrates the successful storage and release of energy for locomotion via passive, mechanically-driven processes.



(C)

Voskhod Spacecraft "Globus" - IMP navigation instrument demonstrates the space heritage of mechanically driven subsystems.

(D)

Daniël de Bruin's Analog 3D Printer - Demonstrates mechanically-driven AM technology which requires no computers, software, or electricity.

(E)

The 10,000 year clock - The mechanical, solar timed and powered clock that is carved out of a mountain, and built to keep accurate time for 10,000 years.

(F)

The Antikythera mechanism - An ancient analog computer designed to predict astronomical positions and eclipses. Dated to 205 BC.

(G)

Mighty Trebuchet at Warwick Castle - The world's largest working siege machine is capable of launching 150 kilogram masses up to 200 meters.

(H)

Large Industrial Gears - Giant gears such as the double helical tooth gear wheel with over a 20 foot diameter have been used to drive large industrial machines since the 1900s.

Figure 2-2: Examples of Mechanical and Analog Devices Useful in the RAMA Architecture

Creating spacecraft from mechanical systems is entirely possible, and given the right mission, is even desirable. NASA NIAC has funded work to JPL under the AREE project (Automaton Rover for Extreme Environments) to develop a Venus rover made entirely of mechanical subsystem capable of surviving the harsh environment on the Venus surface. The RAMA mission class also represents a desirable case for mechanical subsystems. Propulsion systems to move 100-meter asteroids are too large to launch, but can be built in-situ as mechanical mass drivers; flywheels for attitude control are too heavy to launch, but could be constructed within an asteroid to control its spin rate and store energy. It is also possible to create mechanical computation devices for spacecraft that could perform basic avionics-style routines. For missions that require independence from Earth, with no supply of Earth made electronics, the creation of basic mechanical computers may serve as an alternative.

2.2.2 SUBSYSTEM REQUIREMENTS

The performance requirements for each subsystem will depend on the size, mass and type of asteroid they are being built for. A rough estimate of their requirements is provided Table 2-1 for a "typical" asteroid that RAMA might be expected to operate on.

Table 2-1: The general capabilities and performance requirements of each of the asteroids sub-systems. Values reported are for a baseline 100m, 1.5 million tonne asteroid in a near earth orbit.

Subsystem	**Capability**	**Performance Requirement**
Propulsion	Earth intercept maneuver, plus lunar flyby and breaking into cislunar orbit if tug is not available. High enough performance for sufficient asteroid mass to remain after the maneuver is complete	Total ΔV: 100-1000 m/s I_{sp}: 10-100 sec $V_{ejection}$: >100 m/s PMF: 50-85%
Structure	Maintain the asteroid's cohesion while accelerating under propulsive loads, possibly with reinforcement from structural asteroid materials.	10-100 ug's propulsive acceleration, .5-1 g centrifugal acceleration.
Power and Energy Storage	Store all the mechanical energy of the propulsion system, and dispense it at the appropriate time.	1-10 MJ
Attitude Control	Maintain asteroid orientation during maneuver, manage spin rate for artificial gravity control.	5-50% inertial moment of the asteroid
Thermal Control	Maintain adequate temperature range of all hardware on the asteroid, and reject heat due to manufacturing process.	50-500K ~1 MJ, or ~10% of power production
Communications	Position and status reporting to Seed Craft or Earth receiver. Receive and activate flight termination if off course.	Transponder providing range and rate information at ~1AU. 100-1000 W transmitter.
Command & Data Handling	Timing and sequencing of maneuver operations after the Seed Craft departs.	Unknown

2.2.3 ADVANCED MECHANICAL COMPUTERS

The previous section described the driving requirements of the asteroid spacecraft subsystems, which help indicate the constraints on making such subsystems from mechanical means. Of all the subsystems, the most challenging one to create from mechanical means alone are those that require complex computation; notably, GNC and C&DH. In order to address this challenge it is useful to explore the current state of the art of advanced mechanical computers.

By definition, a mechanical computer is a computer built entirely from mechanical components, such as gears, levers and pulleys, rather than electronic components. Early mechanical computers could do basic addition and counting exercises, while later developments saw multiplication, division, and differential analysis. By the 1960's mechanical computers could calculate square roots.

Some notable mechanical computers are the Antikythera Mechanism, circa 200 BC, Blaise Pascal's Pascaline machine of 1642, Charles Babbage's Analytical Engine of 1837, and the Voskhod Spacecraft Globus Navigation Unit of the early 1960's. All of these machines are remarkable in their own right, but the Antikythera Mechanism is uniquely so.

The Antikythera Mechanism, shown earlier in Figure 2-2F, is an astronomical calculator found at the bottom of the sea in 1901. It originally dates back to the 2nd century BC and is a mechanical calculating machine, which predicts the positions of the Moon, Sun and other planetary bodies with surprising accuracy. It took more than 100 years to reveal its secrets to humanity, due to its complex inner structure, as shown in Figure 2-3. The machine made use of 40 gears on 20 axles to track the movement of planets. Techniques such as epicyclic theory, developed by Apollonius and Hipparchus, were used to rotate gears within gears through elliptic routes. The Antikythera Machine could perform addition, subtraction and most amazingly was machined to incredible detail, making it a wonder of mechanical creation to this day.

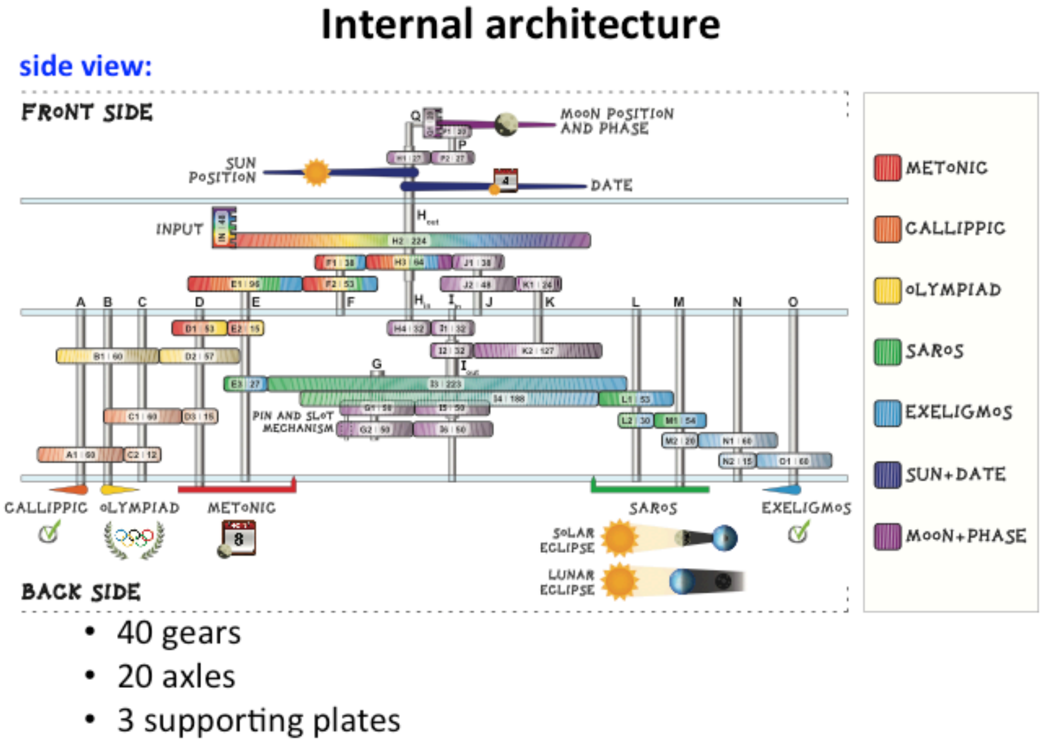


Figure 2-3: The complex gear structure of the Antikythera Machine. © Markos Skoulatos, Eternal Gadgetry

2.2.4 RAMA FUNCTIONAL BLOCK DIAGRAM

The fundamental concept of the RAMA architecture is in the conversion of an asteroid into a spacecraft. In order to do this, the Seed Craft creates spacecraft subsystems out of asteroid materials. For certain asteroid types, material compositions, and mission parameters the best configuration for conversion is to create mechanical subsystems. In all cases studied in this report there are at least some mechanical subsystems that can be made and make sense to make.

Figure 2-4 shows the Functional Block Diagram (FBD) for an asteroid converted into an entirely mechanical spacecraft via the RAMA process. At the heart of the mechanical spacecraft is a 3D printed analog computer that operates on a series of simple gears. The computer is powered by a store of potential energy found in 3D printed springs and flywheels. Mission objectives for the mechanical spacecraft will be fairly basic in nature requiring simple GNC. Flywheel gyros can be 3D printed and will keep the spacecraft on course by feeding momentum data into the analog computer which subsequently commands the propulsion system to propel asteroid materials and impart course corrections.

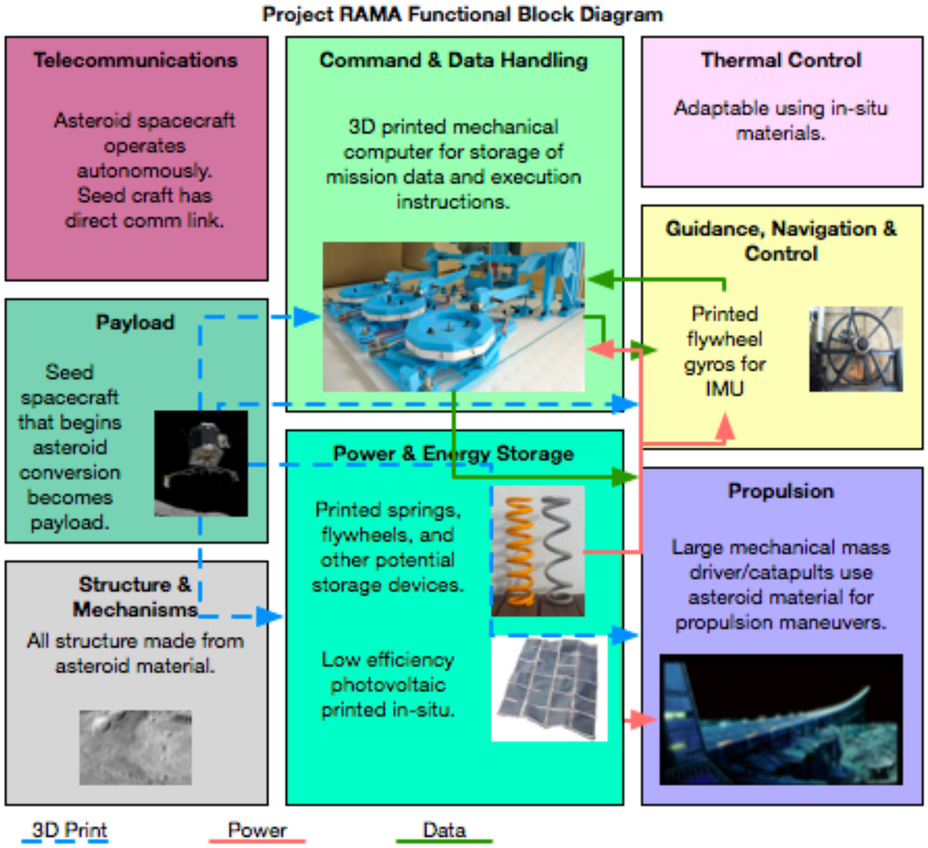


Figure 2-4: RAMA Full Mechanical Functional Block Diagram

Example RAMA Process

Upon asteroid rendezvous, the RAMA Seed Craft analyzes the asteroid, and begins effectively organizing available in-situ resources. The asteroid is broken down and materials are stockpiled as manufacturing feedstocks, as well as viable “waste” mass for propellant. Mechanical energy storage systems (such as examples in Figure 2-2B and Figure 2-2E) are also fabricated on the asteroid, and charged with power from the Seed Craft. Finally, the Seed Craft assembles a unique array of mechanical linkages for the asteroid (like the examples in Figure 2-2 A, C, and F) from ISRU derived components. These will allow for timing and control of the asteroids systems after the Seed Craft has departed for the next target. Some asteroids may require a very complicated series of controls, limited only by the complexity of what the Seed Craft can manufacture before it disembarks to the next asteroid. When the Seed Crafts departs, it triggers the asteroid’s carefully preprogrammed sequence of events, which sets the asteroid on its own path to return to cislunar space without the Seed Craft. Upon arrival in cislunar space, the spacecraft has been significantly lightened by the expenditure of waste material as propellant, and is easily intercepted via the same techniques planned in the crewed portion of ARM.

2.2.5 MECHANICAL SYSTEMS LIMITS

To Build or To Bring? The fully developed RAMA vehicle would require no material input from the Seed Craft. The Seed Craft would provide power and fabrication capabilities, but every component of the finished spacecraft would be built from asteroid materials, allowing the Seed Craft to continue to convert asteroids indefinitely (or until it was rendered inoperable by equipment failure, or obsolete by new asteroid mining methods). However, this capability comes with a tradeoff. We have shown that mechanical components exist that could in theory provide any capability required by the RAMA spacecraft, but the specialized equipment to manufacture the components imposes additional complications and mass penalties onto the Seed Craft's design.

The question should be asked: "Does the equipment required to build this capability locally impose a greater mass penalty than would bringing this component from Earth?" Undoubtedly, the Seed Craft could produce a mechanical computer from asteroid metal, and make it intricate enough to perform orbital calculations to control the Earth return maneuver. But would the complexity and mass penalty of building such a system outweigh the cost of simply bringing an advanced flight computer from Earth, and leaving it on the asteroid? A small spacecraft computer (especially 10-20 years from now) could easily weigh <100g and be the size of a postage stamp, but the equipment to manufacture the mechanical equivalent of such a computer could weigh thousands of kilograms, and impose even higher mass penalties on the power system. Does manufacturing mechanical equivalents locally for every asteroid system really make sense, when equally capable and less massive equipment can just be brought from Earth?

The same can be said for communications and other systems on the low mass end of the spectrum shown in Figure 2-1. Simple radios and communication electronics can no doubt be produced from asteroid materials, but the electronics are not the mass intensive portion of any communication system, the driven elements (the antenna) and the amplifier are.

For contrast, capabilities like propulsion are inherently massive, by the simple physics of their operation. Even an extremely high performance propulsion system with an Isp of 5000 s (far higher than anything under consideration today) would have to consume 22% of the asteroid's mass to affect a modest 1000 m/s in ΔV. The Seed Craft delivering this much mass to the asteroid from Earth would more than double the mass of the Seed craft for even a modestly sized 5m asteroid, and would be completely impossible for an asteroid in the target 50-100m range for RAMA. Clearly, propulsion is a capability that is better provided from asteroid resources than communications or computing power.

Where exactly this tradeoff fall will depend on technology factors we cannot anticipate at present. It will be the responsibility of the designer of future RAMA concepts to perform the Bring vs. Build tradeoff for a given asteroid, considering the expected lifetime of the Seed Craft, and the penalties paid by each extra capability added. For the remainder of this report, it will be assumed that only the four most mass intensive systems of the RAMA craft (propulsion, structures, power storage and attitude control) must be built from asteroid materials. The remaining capabilities can either be provided by the Seed Craft, or built like one of the examples shown in Figure 2-2, but the requirements they place on the Seed Craft / RAMA system are not assumed to be significant enough to change the design. An updated version of the asteroid spacecraft based on this understanding is shown in Figure 2-5.

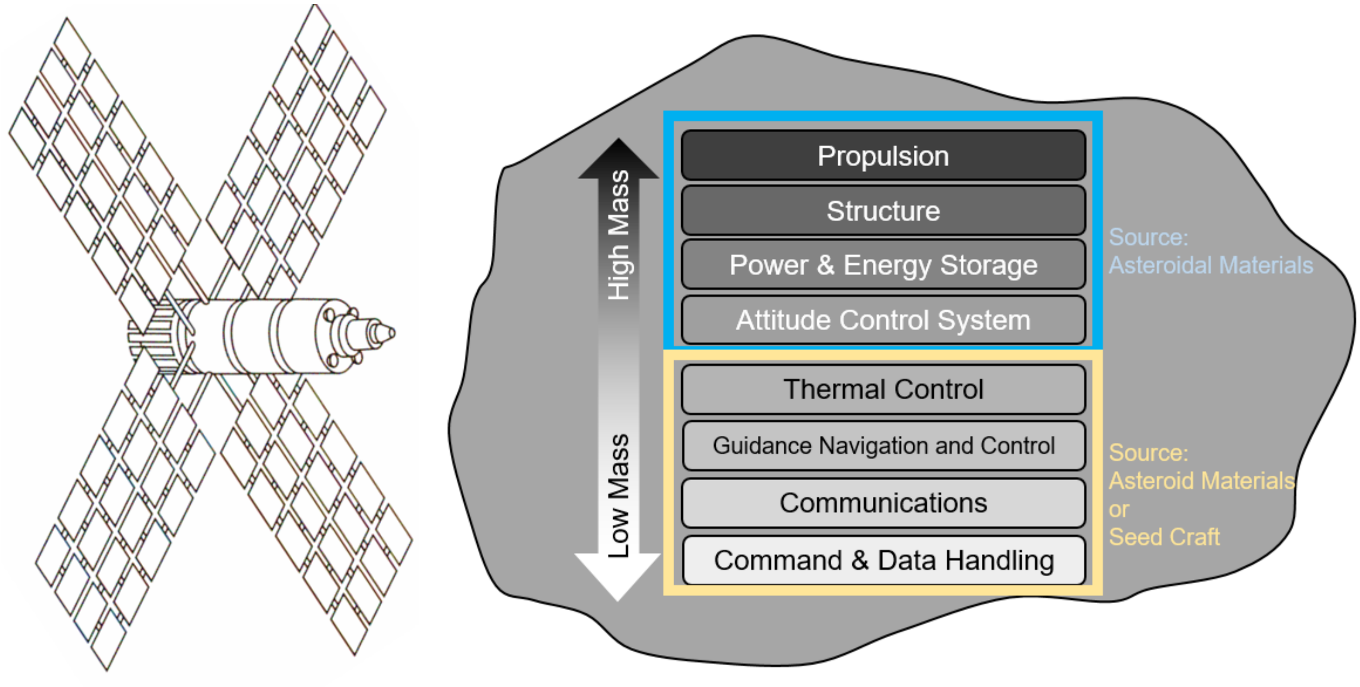


Figure 2-5: An updated version of the asteroid spacecraft requirements from Figure 2-1, showing the source of the materials used to provide each capability as assumed for the rest of this study.

2.3 THE SEED CRAFT

The Seed Craft shown in Figure 2-6, is a more conventional robotic interplanetary vehicle than the RAMA asteroid spacecraft. It contains a high performance low thrust ion engine, along with advanced robotic manufacturing capabilities to produce components of the RAMA vehicle from asteroid feedstocks. The extent of these manufacturing capabilities depends on the target asteroid. For example, a small 10m organic rich asteroid would likely require storage tanks for water-ice, and enough solar arrays to run a ~10 kW electrolysis plant. But a larger 100m metallic asteroid will require additional equipment for processing large quantities of metal ore, including a centrifuge for separation, and a larger solar array capable of powering a ~1 MW electric furnace. Satisfying this large range of requirements is accomplished through having a highly modular Seed Craft.

The Seed Craft is designed around a single common spacecraft bus, incorporating the bare minimum of features required for every mission (propulsion, power distribution and regulation, communication, ADCS etc.) Specific manufacturing modules are then added to the Seed Craft bus to provide the required capabilities for converting a give asteroid. With prior knowledge of the size and composition of the asteroid, the Seed Craft can be fitted with the required manufacturing modules, and fitted with a correctly sized power system before departing cislunar space.

Each module is serviced by a common robotics system, which runs along the length of the interior of the spacecraft. Robotic manipulators are free to traverse the length of the track, transferring materials from one operation to another, and performing maintenance as required. The entire interior of the spacecraft remains unpressurized, allowing the manufacturing operation to take place free of atmospheric contamination.

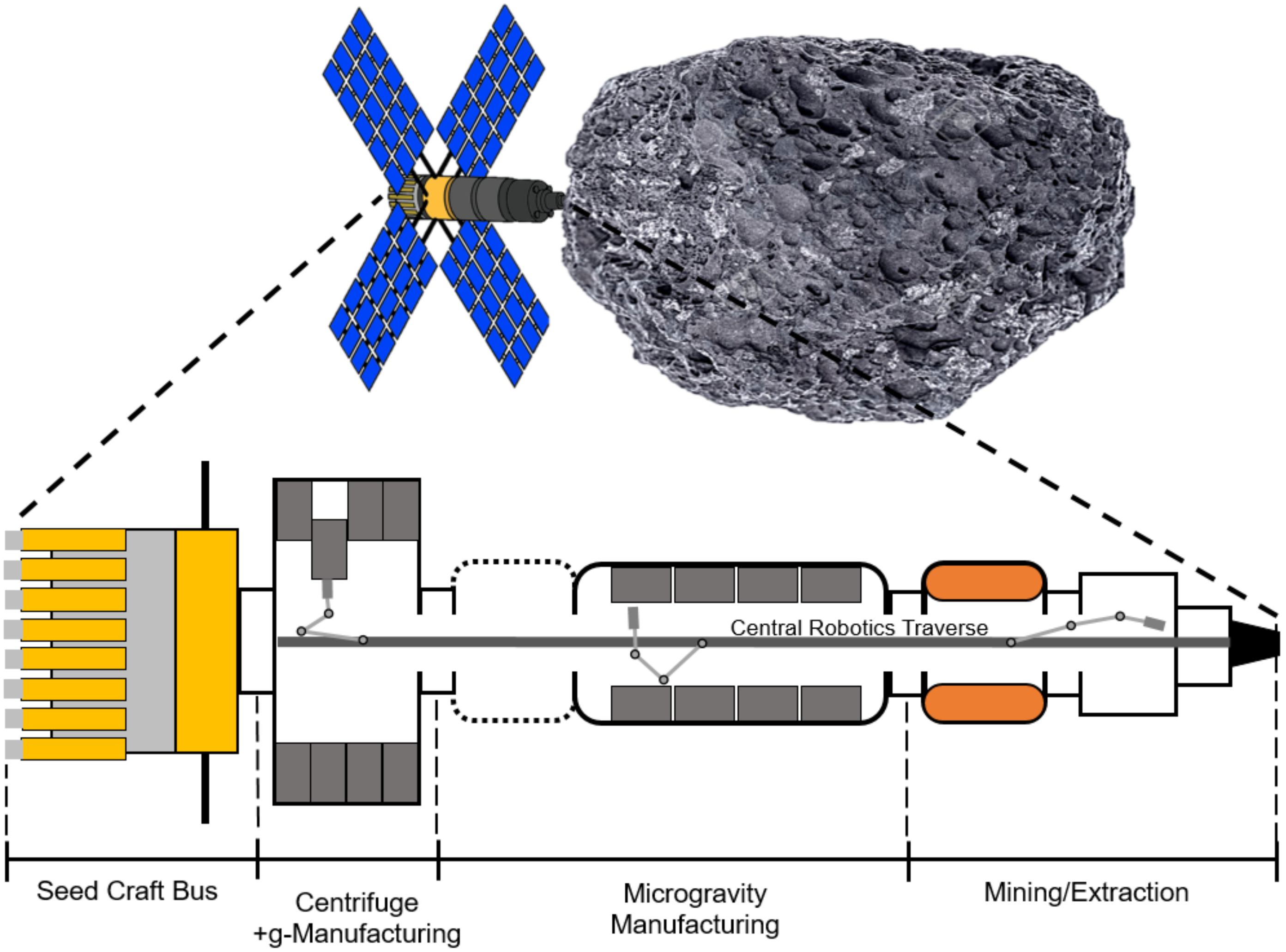


Figure 2-6: Schematic of the Seed Craft Architecture. A modular solar electric propulsion system attached to a common bus. Ahead of the bus are various modules for performing specific tasks required at the asteroid. The module is serviced by a common robotics traverse for transporting materials between operations.

2.4 MISSION IMPLEMENTATION—STOCKPILING MULTIPLE NEAS AT AN EARTH-MOON LAGRANGE POINT

On its maiden voyage, in 2038, the RAMA Seed Craft will use electric propulsion and gravity assists to fly towards and intercept Near Earth Asteroid (NEA) 2009 UY19 which has a well-determined orbit, is 36-163 meters wide, and will be within 15 Lunar Distances (LD) of Earth in 2039 and approximately every 33 years thereafter. After rendezvousing with 2009 UY19, the Seed Craft begins harvesting raw materials from the NEA's surface and subsurface using ISRU technologies pioneered by the NASA KSC Swampworks team and industry asteroid mining initiatives. The Seed Craft will refine the raw material as needed and use the resulting processed feedstock to begin manufacturing necessary mechanical components. As components are made and qualified they are integrated into a large, complex design, which includes subsystems for mechanically driven attitude control, propulsion, energy storage, and autonomous navigation. Eventually, the asteroid itself becomes an autonomous, mechanical, free-flying spacecraft; designated RAMA-1. RAMA-1 would be programmed to slowly adjust its path over time putting it on a new course to the Earth-Moon L5 point where asteroid mining activity is underway, and waiting for the RAMA-1 resources. Once RAMA-1 charts its new orbital path, the RAMA Seed Craft is then sent to a new target asteroid to begin conversion of RAMA-2 and so on until the Seed Craft's end of life or loss of signal. A step by step of the construction process is outlined in Figure 2-7.

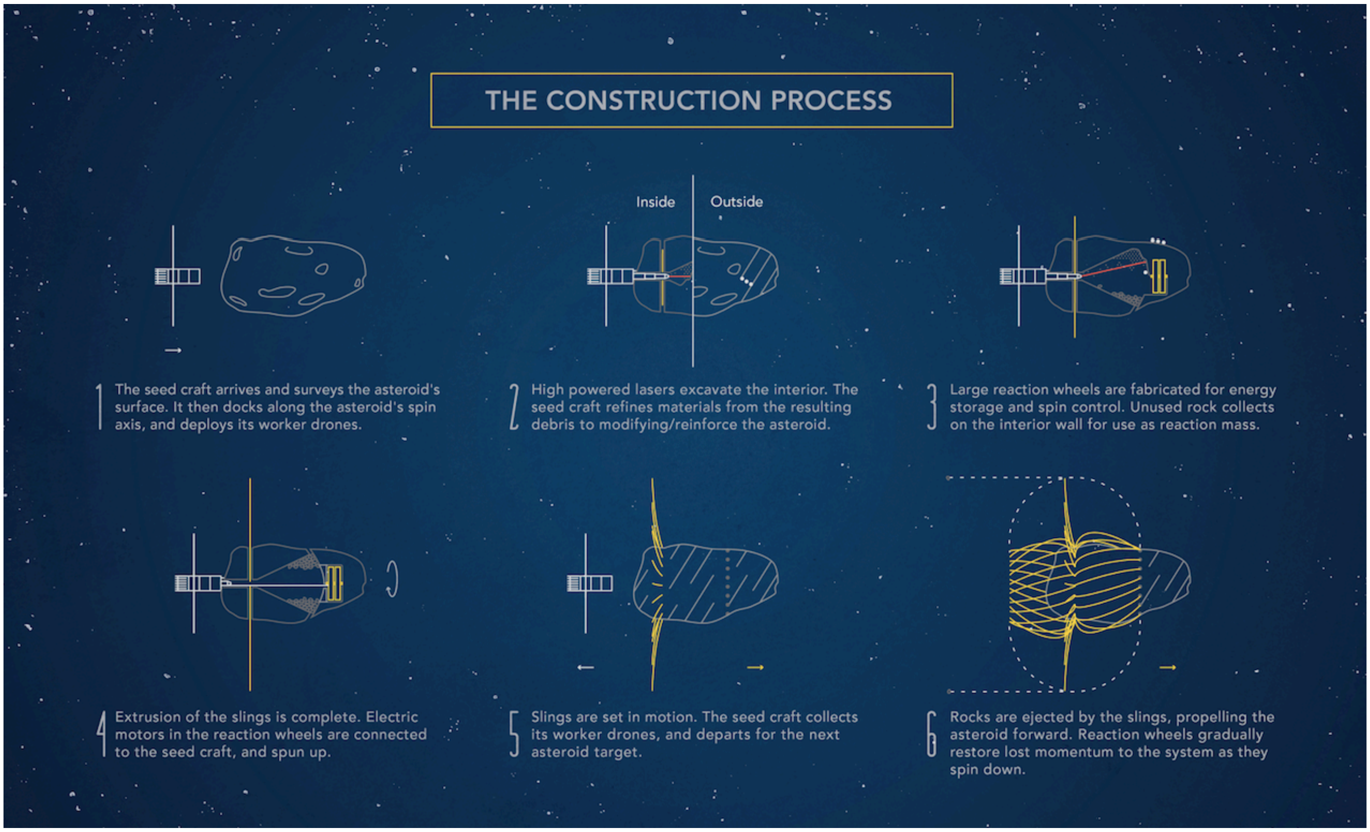


Figure 2-7: The RAMA Construction Process. 1) The Seed Craft arrives at the asteroid and prepares to dock. 2) The Seed Craft has begun mining the inside of the asteroid while extruding the metallic catapult sling arms. 3) The inside of the asteroid is hallowed out with large fly wheels constructed at the bow, worker drones continue to prepare the inside and outside of the asteroid for its mission. 4) The Seed Craft has completed the construction process and has begun to spin up the flywheels using onboard power. 5) The Seed Craft departs from the asteroid after imparting enough momentum to begin sling arm retraction to the loading position. Step 6, the fully functional asteroid spacecraft begins its maneuver.

3 PROJECT RAMA PHASE I WORK

3.1 TECHNICAL APPROACH

The design of a specific RAMA concept involves selecting some top level mission constraints (such as launch window and return mass) and iterating on the design of the Seed Craft, the target asteroid, the return trajectory, and the component RAMA technologies until a design is found that closes on all feasibility criteria. This iterative process is captured in a design tool we have developed called Rock Finder. Rock Finder at present exists as a distributed tool, accessing information from multiple online sources and spreadsheets, and using external applications like the General Mission Analysis Tool (GMAT) and custom scripts written in Octave. The goal is for Rock Finder to be integrated into a single code library or browser application with a cleaner front end that would allow the process to be duplicated by anyone interested in utilization of asteroid resources.

3.2 ROCK FINDER - MISSION DESIGN TOOL

3.2.1 WHY ROCK FINDER WAS NEEDED

Any effort to utilize asteroid resources presents a problem in constrained multi-parameter optimization, a problem analogous to terrestrial resource exploration and mining. In principle, any mineral can be found anywhere on Earth in *some* quantity. But the question of deciding *which* mineral deposits should be extracted and *how* they should be extracted is a question that requires well validated models of every step of the process: From the geology of the region and the processes that formed the minerals, to the cost/yield of the technology to extract and refine it. This is the basis of the distinction between a *mineral* and an *ore*. A mineral is any material that is present in high enough quantities to be detected. An ore is only the subset of minerals that are demonstrably economical to extract under a given set of assumptions about the technology and present market. Calculating which deposits represent ores is the goal of terrestrial prospecting; and it will be of equal importance when applied to the asteroids.

The value of minerals represented by the asteroids far exceeds the value of minerals available in Earth's crust, but the amount of ore currently present in the asteroids is zero. Identifying where in the technological design space the first breakeven point will occur, and to what extent technologies like RAMA can enable that breakthrough, requires quantitative models of the potential impact of any design decision on the extraction of asteroid resources, and it is for that reason that we have developed the Rock Finder tool.

The asteroid mining concept is heavily front-loaded. There is a large and daily increasing dataset of asteroid orbits, and several tools for visualizing this data, as well as for computing launch windows and trajectories to and from various asteroids. But at present, there is no tool for using this data to quickly evaluate a given asteroid's potential return on investment under a given set of technological assumptions. A tool like this is important for any mission based on exploiting asteroid resources, as it helps visualize which technological assumptions are imposing the greatest limits, and which technologies are most in need of development.

No publicly available tool exists at present that is capable of performing the role that Rock Finder is designed for. For example: Suppose an improvement was realized that increased the effective performance of deep space propulsion by 30%. Should such a change be employed to increase the ΔV budget of a spacecraft, thus increasing the number of potentially accessible asteroids? Or would it be better to maintain the existing target base, but use the excess propulsive capacity to bring additional equipment and decrease production time at the asteroid? What if existing models of asteroid populations were revised, and smaller asteroids were found to be more prevalent near Earth than previously predicted? Would the shift to a mining architecture that emphasized distributed mining of a large number of smaller targets be more effective than continuing to mine a small number of large targets? Any one of these discoveries is potentially as disruptive to a future asteroid mining industry as a gold or oil boom in the 1800’s, and who makes their fortunes on the asteroid mining sector will depend on their ability to quickly grasp the implications of new discoveries.

3.2.2 WHAT ROCK FINDER DOES

Rock Finder is a design tool that began as a simple target selector spreadsheet for RAMA. The tool pulls raw data on asteroid orbits from JPL’s small object database and computed transfer trajectories from the Near Earth Object Human Spaceflight Accessible Targets Study (NHATS). It combines this information with top level design assumptions about the capabilities of the Seed Craft, launch window, and processes used to convert the asteroid into the RAMA vehicle, and returns all candidate asteroids that match the required mission profile. Finally, the tool utilizes numerical tools in Octave to compute details of the mission’s trajectory. The tool gradually grew into a complete end-to-end mission simulator, including automatic design optimization of the RAMA crafts subsystem and sizing based on the asteroid’s composition, and exporting of the information to GMAT to perform detailed trajectory planning. A schematic of the tool is shown in Figure 3-1, along with a screenshot of the tool’s Excel based front end in Figure 3-2.

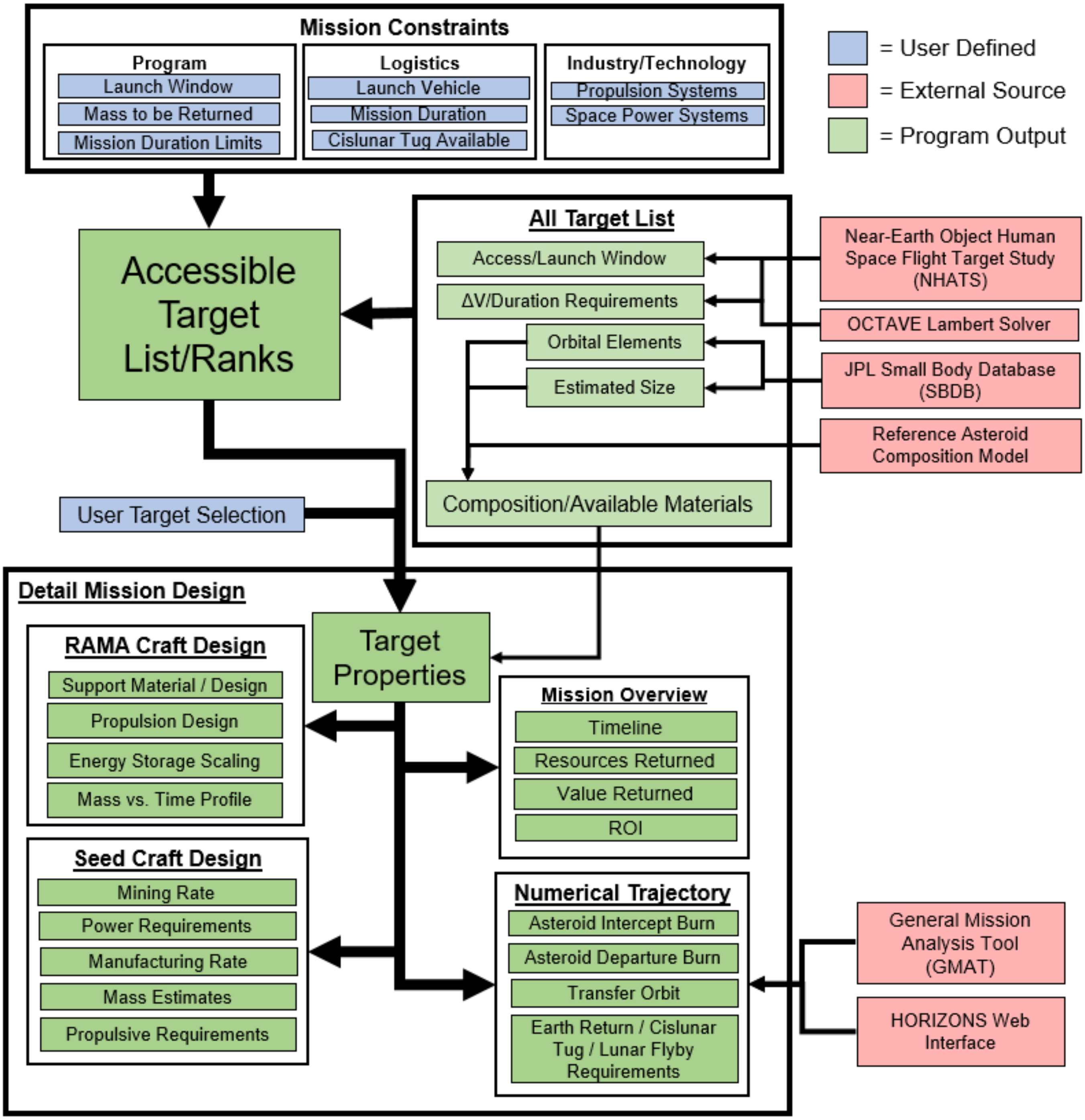
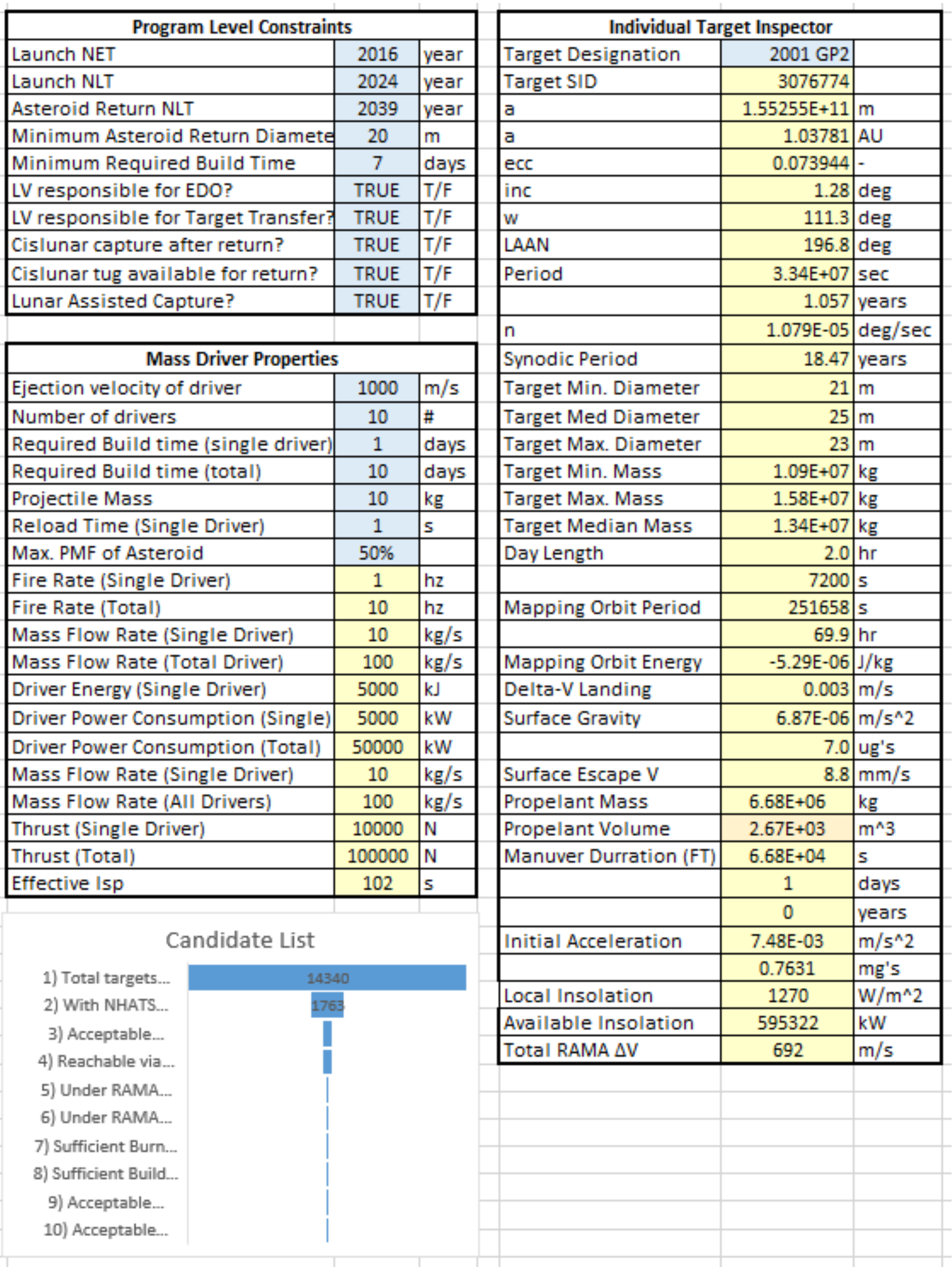


Figure 3-1: Schematic of the back end mission design process for the Rock Finder tool. Mission constraints are specified by the user (blue) which automatically propagate to relevant design parameters for the mission (green), allowing rapid design iteration to produce a workable mission. Items shown in red represent calculations or data input from an external program or website.



Program Level Constraints		
Launch NET	2016	year
Launch NLT	2024	year
Asteroid Return NLT	2039	year
Minimum Asteroid Return Diamete	20	m
Minimum Required Build Time	7	days
LV responsible for EDO?	TRUE	T/F
LV responsible for Target Transfer?	TRUE	T/F
Cislunar capture after return?	TRUE	T/F
Cislunar tug available for return?	TRUE	T/F
Lunar Assisted Capture?	TRUE	T/F

Mass Driver Properties		
Ejection velocity of driver	1000	m/s
Number of drivers	10	#
Required Build time (single driver)	1	days
Required Build time (total)	10	days
Projectile Mass	10	kg
Reload Time (Single Driver)	1	s
Max. PMF of Asteroid	50%	
Fire Rate (Single Driver)	1	hz
Fire Rate (Total)	10	hz
Mass Flow Rate (Single Driver)	10	kg/s
Mass Flow Rate (Total Driver)	100	kg/s
Driver Energy (Single Driver)	5000	kJ
Driver Power Consumption (Single)	5000	kW
Driver Power Consumption (Total)	50000	kW
Mass Flow Rate (Single Driver)	10	kg/s
Mass Flow Rate (All Drivers)	100	kg/s
Thrust (Single Driver)	10000	N
Thrust (Total)	100000	N
Effective Isp	102	s

Candidate List

Individual Target Inspector		
Target Designation	2001 GP2	
Target SID	3076774	
a	1.55255E+11	m
a	1.03781	AU
ecc	0.073944	-
inc	1.28	deg
w	111.3	deg
LAAN	196.8	deg
Period	3.34E+07	sec
	1.057	years
n	1.079E-05	deg/sec
Synodic Period	18.47	years
Target Min. Diameter	21	m
Target Med Diameter	25	m
Target Max. Diameter	23	m
Target Min. Mass	1.09E+07	kg
Target Max. Mass	1.58E+07	kg
Target Median Mass	1.34E+07	kg
Day Length	2.0	hr
	7200	s
Mapping Orbit Period	251658	s
	69.9	hr
Mapping Orbit Energy	-5.29E-06	J/kg
Delta-V Landing	0.003	m/s
Surface Gravity	6.87E-06	m/s^2
	7.0	ug's
Surface Escape V	8.8	mm/s
Propelant Mass	6.68E+06	kg
Propelant Volume	2.67E+03	m^3
Manuver Durration (FT)	6.68E+04	s
	1	days
	0	years
Initial Acceleration	7.48E-03	m/s^2
	0.7631	mg's
Local Insolation	1270	W/m^2
Available Insolation	595322	kW
Total RAMA ΔV	692	m/s

Figure 3-2: An example of a section of the Rock Finder front end, defined in Excel. Shown are the sections allowing top level timeline constraints to be specified (top left, in blue) and the resulting list of available targets

3.2.3 HOW ROCK FINDER WORKS

Reference Asteroid Composition Model: The wide range of compositions present among asteroids prevents easy classification, but a model is required to estimate the composition of an asteroid when spectral data are not available. Such a model can never be more than a rough approximation (no more accurate than a single bulk composition model for all of Earth's surface) but it is useful as a first pass. Based on a combination of meteorite and spectral data [30], the reference composition model shown in Table 3-1 was developed for each Small Main Belt Asteroid Spectroscopic Survey type listed in the JPL small bodies database.

Table 3-1: Reference Composition Model. Developed from meteorite compositions and spectral data.

	Asteroids							
	CI,CM	**CV,CK,CR,CH**	**LL**	**L**	**H**	**EL,EH**	**S-Type**	**M-Type**
Carbon	3%	0.7%	0.1%	0.1%	0.1%	0.4%		
Cobalt			3%	0.7%	0.4%			0.5%
Iron	20%	27%	23%	23%	20%	26%	15%	65%
Water/Ice	20%	7%						
Magnesium Monoxide	11%	14%	14.7%	14.7%	14.7%	12.4%		
Nitrogen	0.25%				0.01%			
Nickle	1%	1%	10%	10%	10%	7%	7%	30%
Olivine	29%	33%	38%	38%	38%	46%	42%	4%
Orthopyroxene						7%	36%	
Phosphorus						4%		
Platinum								0.02%
Sulfur	5%	2%	2%	2%	2%	5%		
Silicon Metal	12%	15%	9%	12%	14%	3%		
Bulk Density (kg/m^3)	1400	1400	1400	2700	1400	1400	2700	9600

RAMA System Sizing: The composition model places limits on what materials are available on a given asteroid and in what quantities. This constrains the capabilities of the RAMA systems, and allows them to be scaled to maximize performance.

An example of the optimization process goes as follows: By specifying the RAMA craft is to be built from a C-type asteroid 20m in diameter, the composition model can estimate that 1172 mT of ice are available on the asteroid. Further specifying that the RAMA craft is to be propelled by a LOX-H2 rocket powered by electrolyzing the asteroid's entire supply of ice constrains the Isp and propellant mass fraction of the RAMA vehicle (340 s, PMF 20%). This is sufficient to constrains the total ΔV capability of the RAMA craft to 76 m/s. The asteroid's known trajectory and computed NHATS results places a required ΔV of 250 m/s for its return to Earth, implying the asteroid must shed 32% of its deadweight before its available ice supply would be enough to propel it back to Earth. The materials budget indicates 33% of the asteroid is composed of Olivine (a silicate rich form of rock), implying a RAMA vehicle fabricated entirely from the asteroid's remaining 27% iron and disposing of all the available rock before departure would be able to return to cislunar space on its own. This further constrains the rate at which the Seed Craft must be capable of processing asteroid material, and thus the size and power requirements of the Seed Craft.

This process is just one example for one selection of parameters; the Rock Finder tool makes it easy for the designer to rapidly compare alternatives and evaluate tradeoffs.

Numerical Trajectory Optimization: Numerical trajectory planning is a computationally intensive process that is unnecessary for checking the basic feasibility of a given mission. But once a specific target is selected, trajectory planning is essential for detailed mission planning, and predicting the system performance. To perform this step, Rock Finder exports the selected asteroid target to the external application GMAT, which in turn imports asteroid SPK files from JPL's HORIZONS tool. GMAT then computes the Seed Craft's and RAMA craft's trajectories, with initial two body impulsive guesses provided by NHATS.

3.2.4 LIMITS AND FUTURE DEVELOPMENT

Economic and ROI Factors: As explained in the asteroid section, no asteroid materials are currently worth extracting for terrestrial consumption under current economic and technological conditions. Rock Finder currently has the ability to evaluate one half of this question, by returning the market worth of a given set of returned materials. Closing the loop and demonstrating what set of assumptions yield a positive ROI only requires developing technology cost models.

Proven vs. Unproven Resources: Rock Finder is currently limited to drawing conclusions only from detected objects in JPLs database. But the majority of asteroids (even among the heavily surveyed NEO population) likely are still undetected. No comprehensive survey has yet been mounted with the ability to detect asteroids with diameters <100m; our only data on asteroids of this size comes from chance detections when they passed relatively close to Earth. Much like with terrestrial prospecting, a significant value of a geological model is its ability to predict where valuable ore reserves are *likely* to be by extrapolating from available data. Statistical models of asteroid formation and their orbital evolution have been used previously to estimates the "unproven" reserves available in the solar system [23]. Rock Finder currently makes no provisions for these unproven reserves when estimating the possible ROI of a given architecture, but is fully capable of doing so given the correct statistical model.

Composition Model: The assumed asteroid composition used to predict available resources is limited by its assumption of identical compositions for identical types of asteroids. In reality, asteroids of the same type can have a range of compositions. An improved composition model would incorporate the statistical nature of each asteroid's composition, considering factors like the asteroid's orbit, and returning a confidence level for each component material. Lowell observatory is expected to release data containing >1000 detailed asteroid spectra, in 2017, allowing more detailed predictions of asteroid composition. Incorporating this data will improve the tool's fidelity.

Automatic Push/Pull of Asteroid Data: Updates to the JPL small body database and the NHATS study are released every 24 hours. Rock Finder currently requires these updates be manually download and inserted into a spreadsheet in order to be reflected in its analysis. A script to automatically pull the data from the appropriate source would increase the tool's effectiveness. NHATS will be rolling out an API in early 2017 that will simplify this process [24].

Once an asteroid is selected, relevant parameters must be manually copied into GMAT and orbital calculations conducted in Octave to produce the full numerical trajectory. GMAT contains the interface to make these updates automatically, and could be scripted to do so.

3.3 ASTEROID SPACECRAFT SYSTEM LEVEL DESIGN

3.3.1 ASTEROID SPACECRAFT DESIGN METHODOLOGY

The methods used to provide each required spacecraft capability depend on the size of the asteroid and the types of materials available. And as explained previously, it is not necessary or even desirable for every function to be built into the asteroid, given the low mass cost of bringing certain systems from Earth. However, since each function could in principle be duplicated with mostly mechanical components, the following analysis was performed on methods to provide each spacecraft capability.

3.3.2 SUBSYSTEM FEASIBILITY ASSESSMENT

The subsystem ranking system takes into consideration a variety of parameters. This includes the given variety of options for the method, viability for in-situ manufacturing, range of asteroid materials that can be used, and overall technology readiness. Table 3-2 provides a detailed breakdown of the ranking system used to evaluate each spacecraft subsystem.

Table 3-2: Subsystem Feasibility Scale. The feasibility of each option is ranked on a scale from 1-5, where 5 is the most feasible. The ranking system takes into account several parameters that evaluates the viability of the subsystem option being useful for the RAMA architecture

Description	Feasibility
Space-compatible technology that has seen prior investigation; modifications for ISRU based manufacturing are possible today with current SOA technology; meets Seed Craft constraints and aligns well with known asteroid availabilities	**5**
Based on ground technology that has been put into use; modifications for space environment are clear and under research; demonstrations exist where additively manufactured or with ISRU materials	**4**
Space-compatible technology that has a large amount of research backing; further modifications for ISRU based manufacturing are clear with path to success, could be constructed from asteroid resources	**3**
Based on ground technology currently being research; modifications for space environment manufacturing unclear with no currently available research	**2**
Subsystem is theoretical or conceptual, with only preliminary research completed; prototyping experiments are over 10 years off; little to no path to create in-situ with Seed Craft	**1**

3.3.3 ASTEROID SPACECRAFT SUBSYSTEM ANALYSIS

Propulsion Subsystem

The propulsion system is in many cases the most pivotal subsystem of the asteroid spacecraft. Arguably many spacecraft subsystems are miniaturizing at exponential rates and thus may not need to be manufactured in-situ; the propulsion system is the outlier. In order to impart large delta-v maneuvers on a 50-100m asteroid, the propulsion is in some way going to come from in-situ means. The analysis in

Table 3-3 shows a variety of methods for creating the propulsion subsystem along with variations on each method, asteroid applicability, and a ranking of each.

Table 3-3: Propulsion Subsystem Options. A variety of options for how to enable the asteroid spacecraft's propulsive capabilities.

Method	Variations	Asteroid Applicability	Feasibility
Mechanical Mass Driver	Mass driver, catapult, Worthwood Quick Release Catapult, trebuchet, spin sling, bi-metallic spring powered catapult (automatic day-night reset), pneumatic ejector, dust and gravel launcher, centrifugal gun, single use mass drivers, single large ejection mass, energy storage flywheels that double as throwing devices, steamboat-style continuous rotation digger/catapult, compressed gas shooting rockets	C	5
Bipropellant Rocket Propulsion	Ice sourced LH2-LOX, NH4, CH4, synthetic biology sourced propellant, 3D printed engines using volatiles as propellant, traditional rocket propulsion with liquid or gasses from asteroid, frictional heat driven chemical reaction	C	5
Monopropellant Rocket Propulsion	Gas powered rocket engine, Ion engine with ground up asteroid as fuel, Pressurized volatiles expelled as gas, Boil volatiles purged through a tunnel, Process rock into fine dust and fire in high velocity streams, Extract gas from solid material and use as RCS, water jet, steam based rocket, steam based spray	S,M	4
Sail Based Propulsion	Solar sail built in-situ, e-sail with 3D printed conductive filament, organic/metallic solar sail constructed from asteroid resources, carbon nanotube/grapheme solar sail, 3D printed thin surface extend out from asteroid as a sail	C,M,S	4
Ablative Propulsion	Laser ablation, shell of mirror to ablate dark side of rock, carve a surface onto the asteroid then target and hit with a high powered laser, solar concentrator to focus light and vaporize materials and volatiles, solar lenses that vaporize asteroid while refining out useful materials for mining, solar lens that is used to eject dust stream	C,M,S	4
Electro-Mechanical Driver	Electromagnetic rail gun, rail gun through center of asteroid's axis of rotation, flywheel powered electromagnetic gun, refined slugs launched on linear induction motors	C,M	3
Non-Propulsive	Eject useful mass to mining outpost and leave main body asteroid in its current orbit, gravity assist with	M	3

	planet, gravity assist with other asteroids or comets, planned collision with other masses		
Robotic Propulsion	Seed craft departure used as propulsive maneuver, ejection of drone Seed Craft swarms, drone swarms that carry their own mass drivers	C,M,S	3
Albedo Based	Selective albedo control, change albedo of very light regions into reflected light, heat responsive louvers	S	2
Explosive	Directed explosions, In-situ creation of explosives used to explode asteroid regions in controlled manner	C,M,S	1

Guidance, Navigation and Control Subsystem (GNC)

The GNC subsystem for the asteroid spacecraft offers many unique opportunities for utilizing in-situ resources in a useful and interesting manner. The results in Table 3-4 reveal several different solutions for creating GNC capabilities using Seed Craft technology. The wide variety of options may of course be narrowed down when analyzing specific mission scenarios.

Table 3-4: GNC Subsystem Options. A variety of options for how to enable the asteroid spacecraft to have guidance, navigation, and control capabilities.

Method	Variations	Asteroid Applicability	Feasibility
Flight Control – Spin	Reshape asteroid to control spin, fly wheels, fly wheel powered gyros, unprocessed giant portions of asteroid spin as reaction wheels, gyro/centrifuge combo, de-spin by using asteroid spin to advantage	C,M,S	5
Flight Control – Volatiles	Micro-propulsion using volatiles, using propulsion tangent to the surface for torque, small explosives, selectively explode asteroid to alter center of rotation	C,M,S	5
Navigation Calculation – ISRU	3D print circuits, rudimentary mechanical application delivery controller (ADC), 3D print photo sensors to make basic star tracker, solar system designed by gear system, bi-metallic strips for mechanical computer vector input as 8-bit value	C	5
Obviate the Need for GNC	Perfect the initial momentum transfer, Seed Craft creates perfect clock, gears sling rocks in certain directions at certain times, Seed Craft pre-programs all GNC	C,M,S	4
Guidance – Photo Sensors	Elements that turn on in sunlight and off in the dark, bimetallic strips via sun slits, sun spotter plus Earth laser, 3D print photo sensors to make basic star tracker	C,M,S	4

Flight Control – ISRU	Little mass ejections, use RAMA to send multiple asteroids into each other to create vector to Earth-Moon L5	C,M,S	4
Flight Control – Sails	Solar sails, e-sails with metallic wires that alter length to change direction and course	C,M,S	4
Flight Control – Albedo	Albedo adjustment to get thermal radiation spin effects	C,M,S	3
Guidance – Physical	Create metallic whiskers that act as feedback sensors	M	3
Flight Control – Gravity	Use known gravity pathways through solar system to create a active GNC free trajectory	C,M	3
Navigation Calculation – Bring It	Bring micro-miniaturized electronic navigation devices on Seed Craft and install on asteroid	C,M,S	2
Navigation Calculation – Dead Reckoning	Silk road dead reckoning between terrestrial craft that reprograms course	S	1

Command and Data Handling Subsystem (C&DH)

A leading question for the Phase I study was the true necessity for a C&DH capability on the asteroid spacecraft: Does the asteroid spacecraft need to be able to communicate to and from Earth? Through investigation of mission scenarios the study team found instances where C&DH would be desired as well as instances where a fully automated and cut-off from communications architecture would be sufficient to achieve mission goals and objectives. Table 3-5 summarizes the variety of C&DH options when for the RAMA architectures that need such a subsystem.

Table 3-5: C&DH Subsystem Options. A variety of options for how to enable the asteroid spacecraft to have command and data handling capabilities.

Method	Variations	Asteroid Applicability	Feasibility
ISRU Computer - Electronics	Make 1970s era TTL semiconductors, use metal on asteroids to build circuit boards, make miniature RISC for processor and then compile to bytecode, use BMS and asteroid rotation as system clock, insulate conductive traces on surface of asteroid, 3D print wires, traditional electronic wiring, Seed Craft lays out wires across asteroid	C,M,S	5
ISRU Computer – Mechanical	Mechanical logic processor, bimetallic strips and sun act together for differential code execution, printed clock sundial code execution, print collimator, shadows used for computation	C,M,S	5
Remote Control – Light	Use lasers directed from Earth, laser or Sun heat used to turn orientation into a mechanical signal,	C,M,S	4

and Heat	synchronous communications with spin rate and heat, track asteroid from Earth and send position with pulses hitting thermal expansion, use mirrors for old semaphore style communications with Earth		
Remote Control – Radio	Six masts line of sight RF, mesh network LoS RF for swarms, short wave RF, build a crystal radio in-situ	C,M,S	4
Bring Computer Along	Seed craft deploys micro-miniature avionics on each asteroid, advantage is that in 20-30 years computers the size of a thumb nail will be highly advanced	C,M,S	4
Obviate the Need	Hard code course with the Seed Craft, Seed Craft can code a mechanical computer that executes on that code without ever adjusting the code	C,M,S	3

Energy Production and Storage Subsystem

Like the propulsion subsystem, there are no RAMA missions in which some level of energy production and storage are not needed, and in the cases that it is needed the subsystem is too massive for launch from Earth on the Seed Craft. Therefore, it was critical to analyze the variety of ways to create energy production and energy storage subsystems in-situ using the Seed Craft's capabilities. Table 3-6 presents the results of the analysis. The table presents solutions for both fully mechanical as well as electrical methods; all of which have the potential for in-situ creation from asteroid materials.

Table 3-6: Energy Production and Storage Subsystem Options. A variety of options for how to enable the asteroid spacecraft to have energy production and storage capabilities.

Method	Variations	Asteroid Applicability	Feasibility
Mechanical (Storage)	Printed springs, wind up coil springs, flywheel and spring system combo, pure fly wheels, fly wheels pre-spun by Seed Craft, giant reaction wheels used for both energy storage and stabilization, spin up flywheels with large impulse and use that for power, pneumatics with gas taken from asteroid	M,S	5
Mechanical (Generation)	Geothermal power, tidal power, orbital energy collection, move H2O to center of asteroid and use turbines on the edges with centrifuge to create energy	S,C	5
Solar Power (Generation)	Create solar photovoltaic cells in-situ for power generation	C	5
Electrochemical (Storage)	Build batteries from volatiles, solid state fuel cells, solar powered flywheel provides energy to system as it is used	C	5
Thermal (Transmission)	Use heat pipes to transfer energy	C,M,S	5

Thermal (Generation)	Simple power plant, heat engine, utilize the latent heat from phase change or heat capacity	C,M,S	5
Thermomechanical (Generation/Storage)	Concentrate sunlight, store in the heat capacity of rocks, use mirrors to concentrate energy for steam, solar sails on one side to wind a spring, bi-metallic strips on both sides of asteroid wind the springs in the dark, bi-metallic springs that charge during the day and relax during the night, solar concentrator that uses heat to pressurize the volatiles, use of a basic thermocouple between extreme hot and cold areas to generate electricity	C,M,S	4
Chemical (Generation)	Mine the volatiles and use for power generation	C,M,S	4
Nuclear	Seed craft brings RTGs for power supply	C,M,S	3
Seed Craft Exclusive	All energy generated by the Seed Craft, Seed Craft makes and compresses springs, Seed Craft uses solar PV during conversion process and dumps extra energy into asteroid derived energy storage	M,S	3

Subsystem Connections

The final subsystem analyzed in this study was the connections from one subsystem to another. The analysis shown in Table 3-7 lists a variety of options for enabling asteroid spacecraft subsystems to connect power and data through mechanical and in-situ created means.

Table 3-7: Subsystem Connection Options. A variety of options for how to enable the asteroid spacecraft subsystems to connect and transfer data to one another.

Method	Variations	Asteroid Applicability	Feasibility
Mechanical Gears, Pulleys, Levers	Gears and chains, belt driven systems, worm gear systems, wires on pulleys, fiberglass tethers and belts derived from asteroid materials	C,M,S	5
Fluid Pipes to Send Signals	Fluid pressure linkages, fluid muscles	C	5
Vibration and/or Resonant Frequency (Tuning Forks)	Generate asteroid quakes to transfer signals	C,M,S	5
Light Shadows	Utilize light and shadows to transfer information from subsystem to another	C,M,S	5
Fiber Optics	Create fiber optics from asteroid materials and use sunlight to transfer information through optical fibers	C,M,S	5
Pneumatic Digital	Harness asteroid volatiles to create a pneumatic	C,M,S	4

Communication	actuator for sending digital commands		
Programmable Matter	Anticipate trends in programmable matter that will be available in the RAMA suggested timeframe and use programmable matter to create nanoscale intelligent control	C,M,S	4
Mini Projectiles	Launch small projectiles off the asteroid in a manner that other subsystems can measure projectile launches in a way of communications	C	3
Orbiting Satellite to Relay Digital Signal or Light Via Mirror	Seed craft deploys a small orbiting satellite around the asteroid to relay digital signals off of mirrors or corner cube reflectors installed on the asteroid surface	M,S	2
Thermal Expansion/Contraction	Modify the asteroid in such a way that its thermal expansion and contractions can be used to relay information	C,M,S	2
Vaporize Volatiles Selectively for Input	Combined with heat pipes or pressure tubes, volatiles can be vaporized in a selective manner to transfer data from one subsystem to another	C,M,S	1

3.3.4 SELECTED METHODS

Every one of the technologies listed in the previous section represents a possible way to provide the capabilities the RAMA craft requires. But the materials available in the reference composition model do suggest which methods would be practical on which asteroids. For example, an S-type presents virtually no water/ice, requiring a mechanical method of propulsion. A C-type would be metal poor, meaning fabricating large electromagnetic elements is probably not realistic. Some results incorporating these limits are shown in Table 3-8.

Table 3-8: The suggested means of accomplishing some of the RAMA crafts required capabilities on a C, S and M type asteroid.

Asteroid Type	**C**	**S**	**M**
Propulsion	Water to LOX/H2 Propulsion	Mechanical Mass Driver	Electric Mass Driver
GNC	Selective Albedo Control	De-spin Masses	Electrodynamic Whiskers
Energy	On board Seed craft	Silicon PV Panels	Flywheel/Metallic Spring

3.4 ISRU MANUFACTURING ASSESSMENT

3.4.1 IN-SITU RESOURCE AVAILABILITIES AND OPPORTUNITIES

While rare metals like platinum and palladium are available in the asteroids, the true value of asteroid resources does not come from the presence of valuable trace materials. **The value of the asteroids comes from the availability of common materials without the need to ship them from Earth.** Launching material from Earth to cislunar space costs ~$40000/kg, meaning that material, once it is delivered from Earth to cislunar space, is literally as valuable as gold.

For any major project in cislunar space (such as the construction of large habitats or radio telescopes) it is impractical to ship bulk materials from Earth at that rate. Bulk materials, if available in space, will be exploited in space, with launch capacity from Earth being reserved for complex equipment and trace materials that cannot be obtained without Earth's complex industrial base. Even assuming futuristic advances in technology like space elevators, the energy required to ship materials from Earth's surface to cislunar space will always be higher than the energy required to ship the same material from the asteroids, implying that the theoretical minimum cost of sourcing the materials from Earth will always be higher.

This is not currently the case because mining and refining resources on Earth is a cost optimized practice with several thousand years of development behind it. The process of extracting resources from asteroids is undeveloped, and not cost competitive yet with terrestrial mining. But assuming the process of extracting and refining asteroid materials can be made competitive with the cost of extracting and refining terrestrial resources, a clear market will develop for common materials like ice and iron in cislunar space.

Critical capabilities are missing at every step of the process. The process can be thought of in terms of the following 9 steps, adapted from J. Lewis shown in Table 3-9.

Table 3-9: The Process of Extracting Resources. A list of what is involved in terrestrial and asteroid mining at each of J. Lewis's 9 steps of resource extraction.

Process	Earth Resources	Asteroid Resources
1) Finding	Geologic Surveying Ground Penetrating Radar On Site Mineralogy Testing	Astronomical Surveying Remote Sensing
2) Mapping	Static Data	Spectral Analysis Time Dependent Data
3) Analyzing	Lab/Field Testing Mass Spectroscopy Chemical Processing	Photometry Spectroscopy
4) Modeling	Geochemical Processes	Dynamic Numerical Modeling N-body Collision Dynamics
5) Excavating	Human-In-The-Loop Decision Making Human/Robot Cooperative Operations Mechanical Sorting Gravity Fed Separation Open Containment	Autonomous Decision Making Fully Robotic Operations Electromagnetic Sorting Microgravity Processing Fully Contained Hard Vacuum
6) Transporting	Surface Transport Cost proportional to Distance Travelled	Interplanetary Transport Cost proportional to ΔV
7) Enriching	Mechanical Processes	Thermal/Chemical Processes
8) Extracting	Mechanical Processes	Thermal/Chemical Processes

None of the technologies employed in terrestrial mining can be directly applied to asteroid mining. Implicit in the development of all terrestrial mining technologies are certain assumptions that are not valid in the context of asteroids, such as:

1) The presence of humans to correct mistakes and make decisions.
2) An industrial base for providing replacement parts and equipment.
3) Gravity to provide a buoyant force for the settling and separation of materials.

These differences render all terrestrial mining experience inadequate, and present technological barriers that must be overcome before asteroid resources can capitalize on its energetically advantageous position in the solar system.

Resource Overview: Asteroid compositions mimic the composition of Earth, but without the benefits of gravity and geologic processing that have concentrated and dispersed materials throughout Earth's interior. Asteroids thus contain abundant supplies of iron/nickel (present in Earth's core) silicates and oxides (present in Earth's mantle) and water-ice and other volatiles (present on Earth's surface). These asteroid resources can be combined to produce effectively anything that a maturing space civilization requires. Examples of this are shown in Figure 3-3.

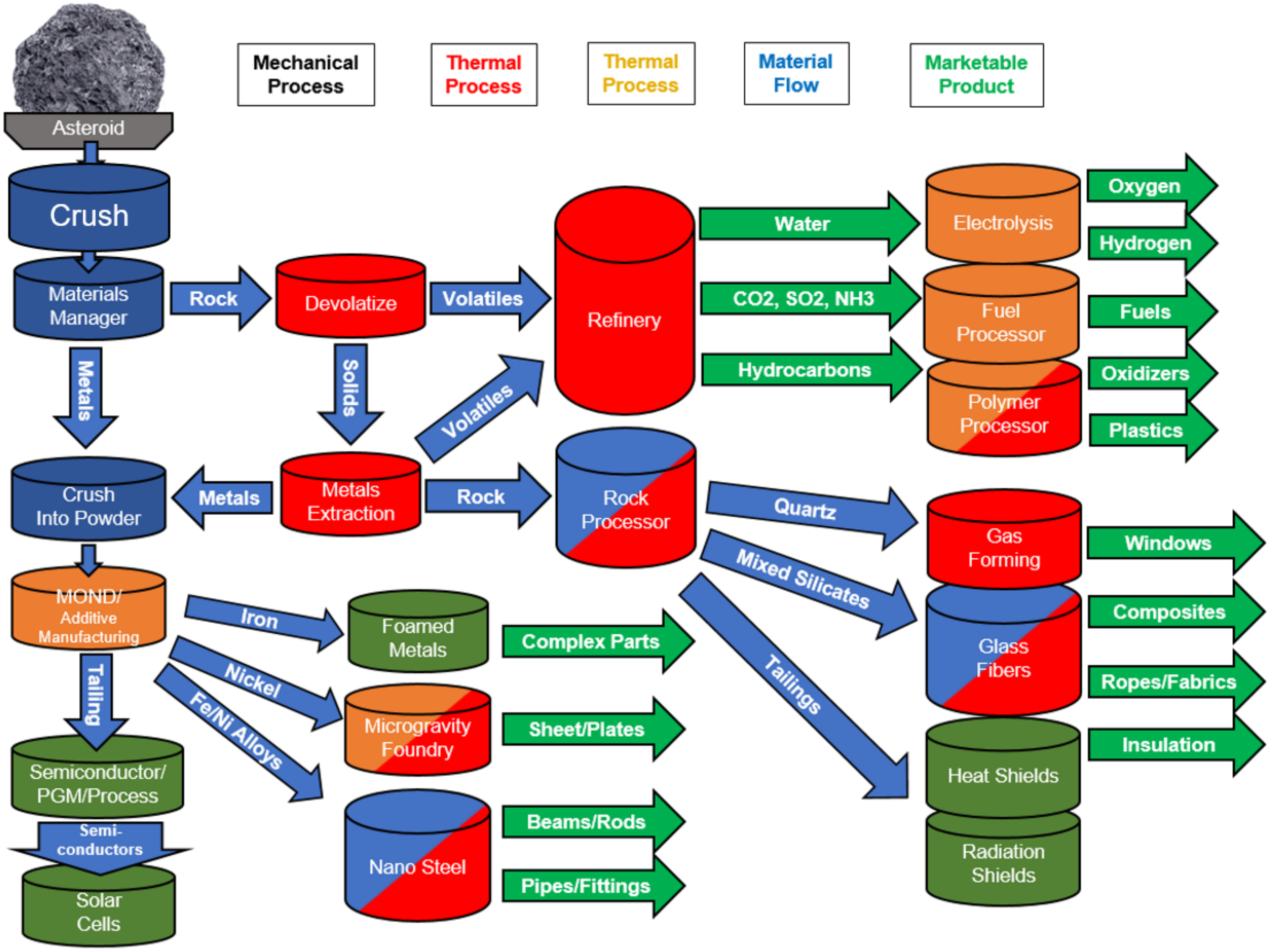


Figure 3-3: The range of finished products and required processes for a comprehensive asteroid mining mission. The actual options available on a given asteroid will be limited to a small fraction of this schematic due to the lack of certain materials. Adapted from J.L Lewis "Mining the Sky", Figure IX2.

The range of processes illustrated in Figure 3-3 shows why the modular design of the Seed Craft is essential. An M-type asteroid for example is not expected to contain any significant quantities of volatiles. Any capabilities on the upper branch of the chart would represent wasted mass of the Seed Craft. By contrast, a volatile rich but metal poor C-type asteroid would be restricted by material availability to an upper branch of the tree as shown in Figure 3-4.

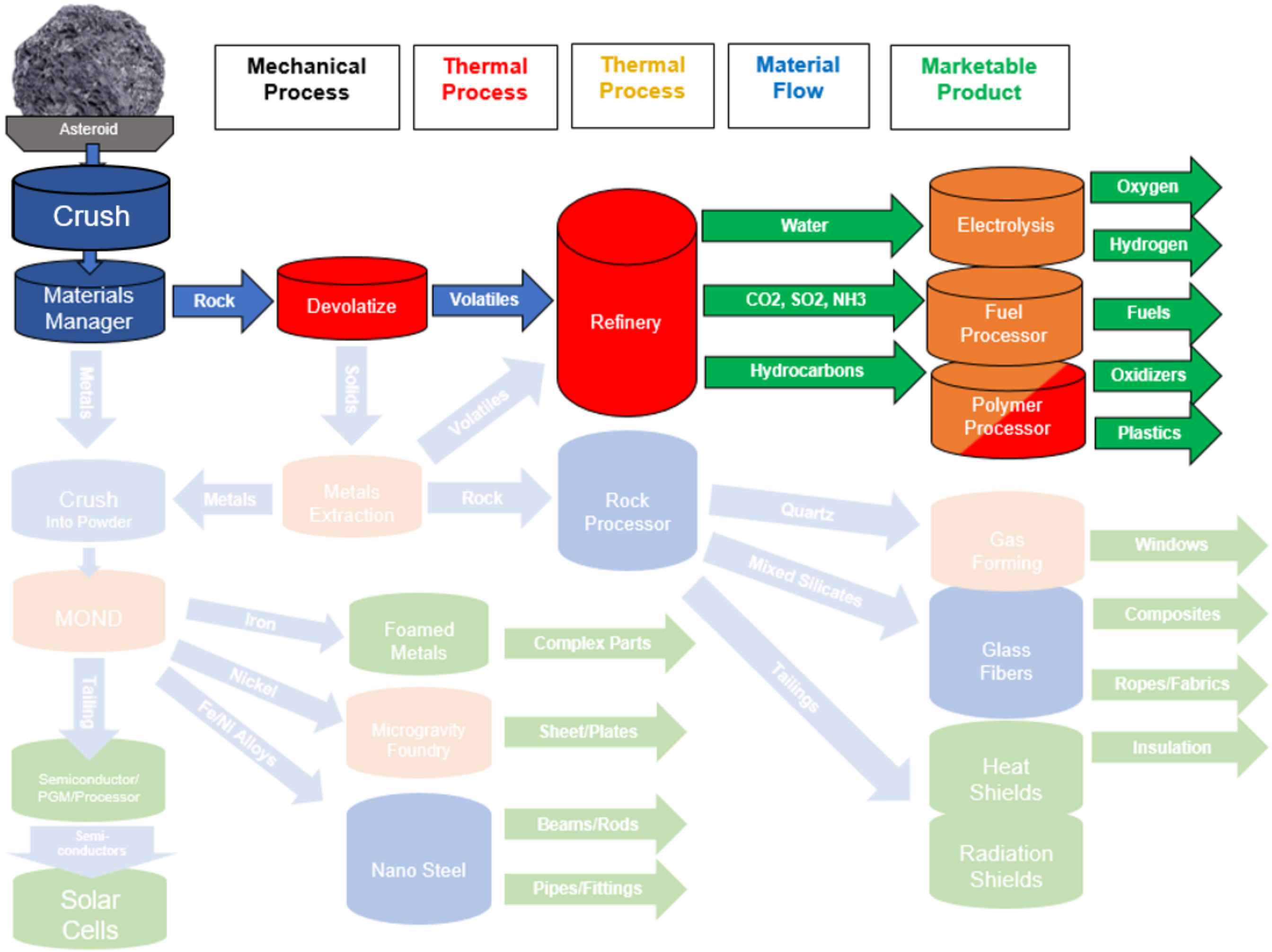


Figure 3-4: The range of finished products and required processes available on a C-type asteroid. The prevalence of organics and volatiles leads to the exclusion of metal based manufacturing methods in favor of polymer structures and chemical propulsion systems. Adapted from J.L Lewis "Mining the Sky", Figure IX2.

Even limited to these options, the C-type asteroid has the materials to produce high performance rocket propellant, which can be used to propel the RAMA spacecraft to new locations. The availability of polymers also permits composite structures to be manufactured along with the crushed rock and regolith, forming a composite material with excellent tensile and compressive strength. A prototype of composite ISRU based additive manufacturing was created during this study shown in Figure 3-5. A spring loaded propellant cannon was created using polymer based additive manufacturing methods shown in the left of the image. On the right side of the image is a JSC-1A regolith simulant combined with a polymer to create a composite structure with functioning gearbox inside.

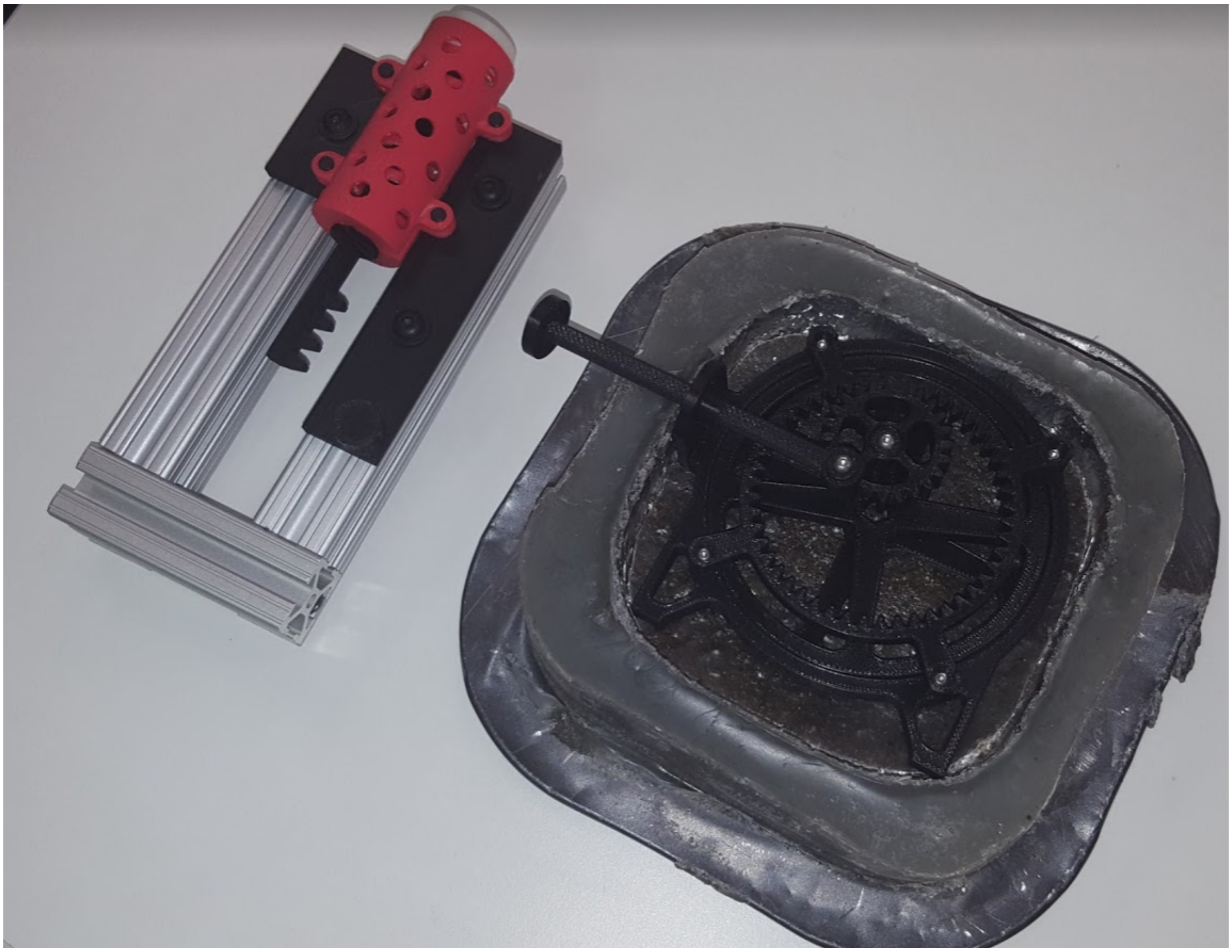


Figure 3-5: An example of a composite part manufactured by combining a regolith analog with a polymer binder. The resulting structure exhibits excellent tensile and compressive properties, and can be bonded with a fully polymer part (shown inserted as a gear and piston assembly manufactured from ABS plastic)

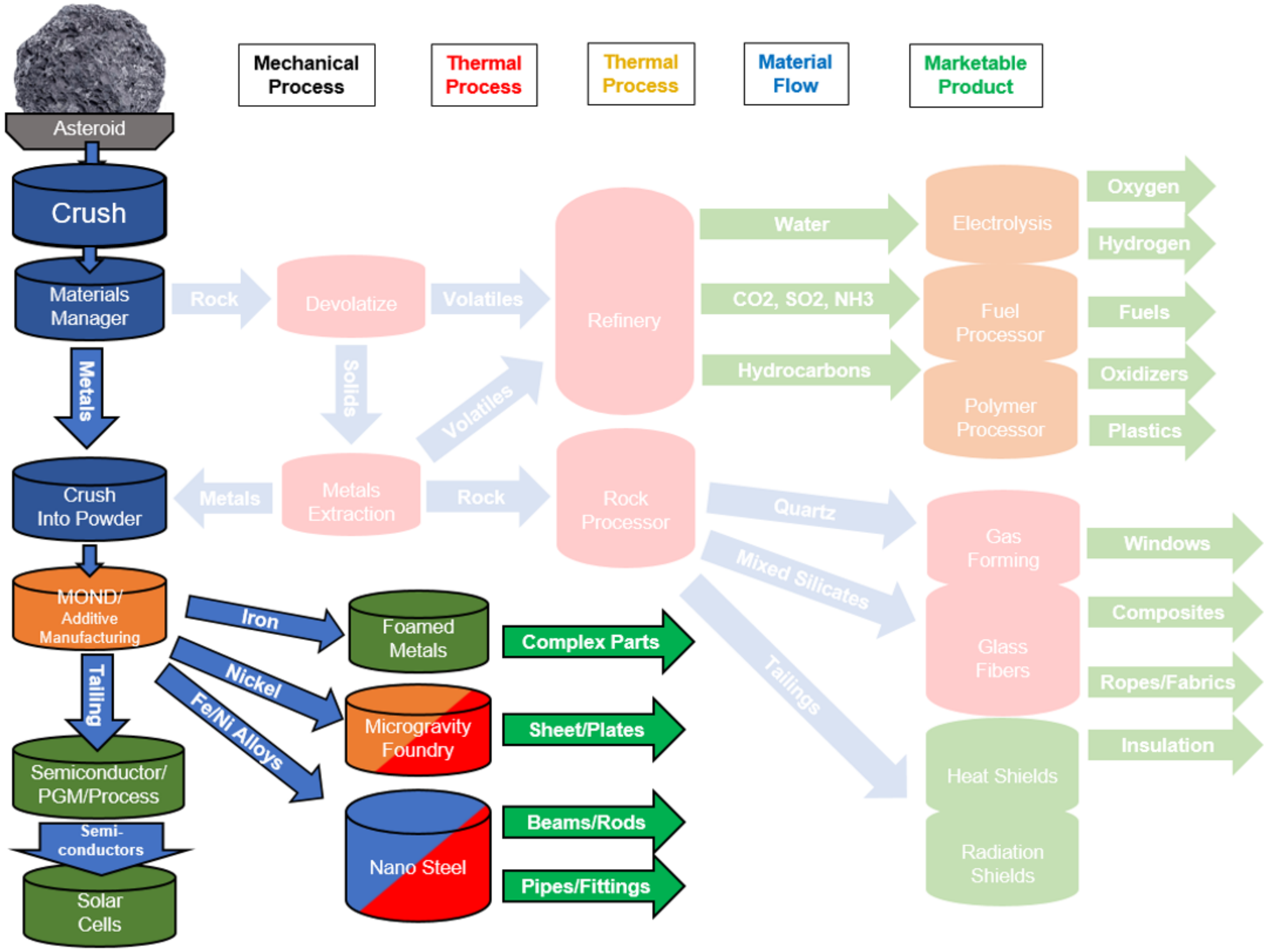


Figure 3-6: The range of finished products and required processes available on a M-type asteroid. Adapted from J.L Lewis "Mining the Sky", Figure IX2.

A metal rich asteroid would be constrained to the lower left side of the chart as shown in Figure 3-6. Manufacturing techniques on the M-type asteroid would employ methods such as the carbonyl based Mond process and powder sintering methods to produce strong metallic structures. Propulsion options are much more limited, but one possibility would be the use of surplus metal to produce an electromagnetic cannon powered by locally manufactured photovoltaics.

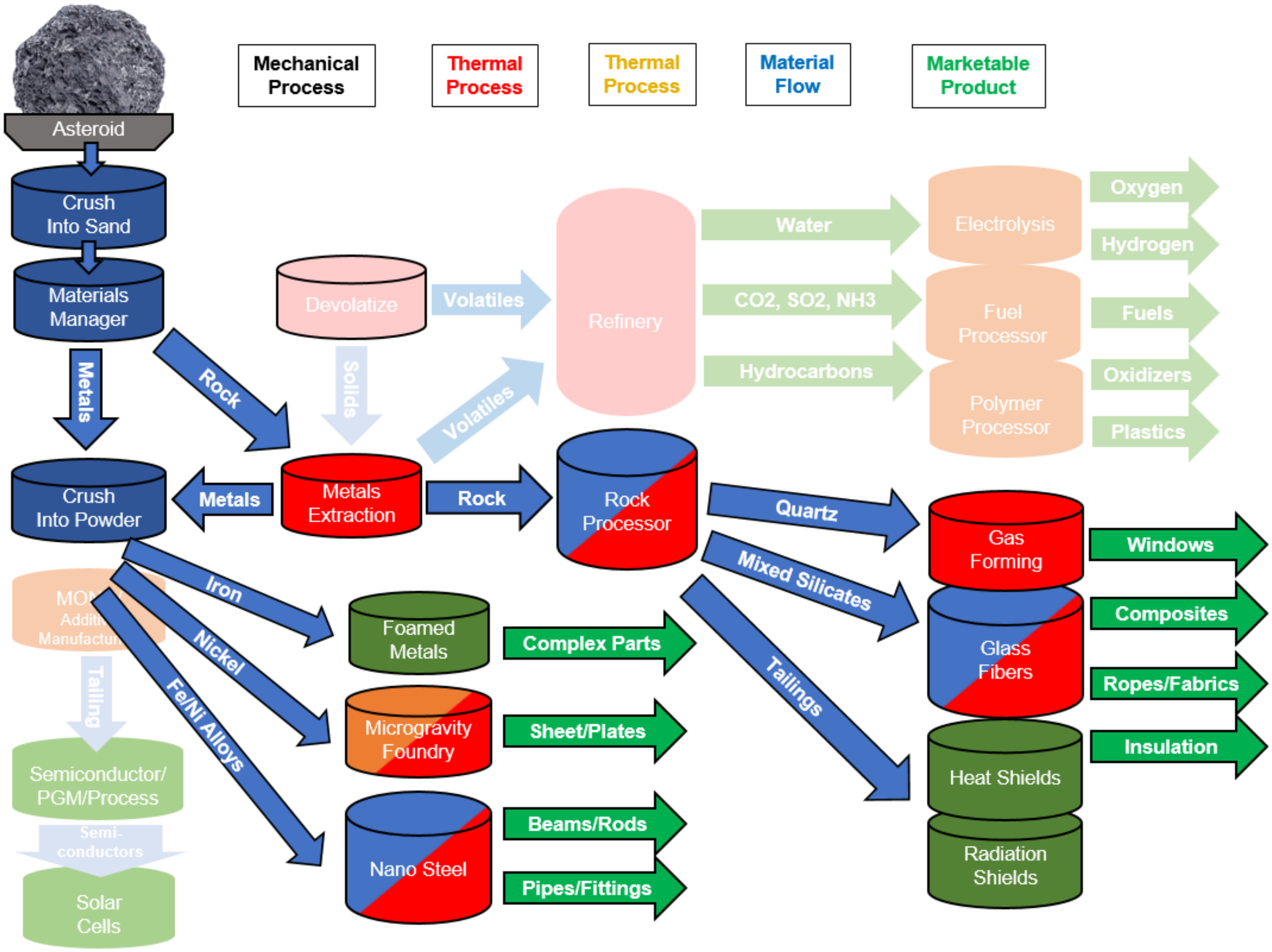


Figure 3-7: The range of finished products and required processes available on a S-type asteroid. Adapted from J.L Lewis "Mining the Sky", Figure IX2.

A stony asteroid process, shown in Figure 3-7, presents a middle ground between the C and M types, permitting the use of both metals and stones as manufacturing materials. Propulsion options include the use of excess stone as projectiles in a high strength steel sling.

Additive manufacturing technologies provide unique opportunities for the S-type asteroids. For example, additive manufacturing represents an instance of the fully autonomous robotic operations required by Step 5) Excavating. For manufacturing complex metallic parts without the support of a planet scale industrial base, additive manufacturing also provides an alternative to the Mond Carbonyl process. It is for these reasons that the current study focuses on the S-type asteroid for RAMA mission design.

3.4.2 IN-SITU MANUFACTURING TRADE STUDY

In-Situ Manufacturing Trade Study Methodology

A trade study was performed on the variety of in-situ manufacturing technologies that are available or in development for use with the RAMA architecture. The study looked at manufacturing methods that are or can be adapted for additive manufacturing processes as well as those technologies that can be automated. Only manufacturing technologies that can work with candidate materials found on asteroids were considered. Finally, a set of evaluation criteria was created to compare each technology against the other. The evaluation criteria focused on six unique aspects: Current TRL, TRL in 20 years, Cost and Potential Success of R&D, Total Cost of Method Once Developed, Shape Error Tolerance in Manufacturing, and Asteroid Type Applicability.

Evaluation Criteria

In order to properly evaluate a variety of manufacturing technologies for future applicability with the RAMA architecture six unique criteria were selected which together give a holistic look at each manufacturing method in comparison to one another. The six criteria were; Technology Readiness Level (TRL), TRL in 20 years (TRL +20), Cost and Potential Success of R&D, Total Cost of Method, Shape Error Tolerance, Asteroid Applicability. The basis for how each criterion was evaluated is described below.

Technology Readiness Level

The first two criterion, TRL and TRL +20 years, are evaluated using the accepted NASA nomenclature for TRL. Shown in Table 3-10, the TRL of each manufacturing method is ranked based on maturity an readiness for use in the space environment. Given that the RAMA architecture is a forward looking program with a 20 year plus horizon, it is critical to not just evaluate the current TRL of a method but also to analyze the expected TRL maturity by the time the first RAMA missions are expected to take place.

Table 3-10: Technology Readiness Level Description

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

Cost and Potential Success of R&D

The estimates for the R&D costs of each manufacturing method were calculated by carefully analyzing each method across a set of factors: Comparison to other space-based manufacturing systems developed by MIS, analysis of similar systems created by other organizations, projected time frame for availability, and general subject matter expertise within the MIS team. Table 3-11 provides the ranking metrics for the cost and potential success of each manufacturing method as it pertains to the RAMA architecture.

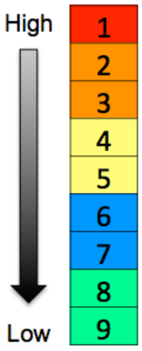
Table 3-11: Cost and Potential Success of R&D. This metric is based on associated costs and success metrics for accomplishing the RAMA architecture.

Description	Ranking Factor
Space-compatible technology that has seen prior investigation; modifications for ISRU based manufacturing are possible today with current SOA technology; meets Seed Craft constraints and aligns well with known asteroid resources.	9-10
Based on ground technology that has been put into use; modifications for space environment are clear and under research; demonstrations exist where additively manufactured or with ISRU materials	7-8
Space-compatible technology that has a large amount of research backing; further modifications for ISRU based manufacturing are clear with path to success, could be constructed from asteroid resources	5-6
Based on ground technology currently being research; modifications for space environment manufacturing unclear with no currently available research	3-4
Method is theoretical or conceptual, with only preliminary research completed; prototyping experiments are over 10 years off; little to no path to create in-situ with Seed Craft	1-2

Total Cost of Method

The total cost of each method was evaluated using a set of pre-described evaluation criteria as detailed in Table 3-12. The cost criteria assess expected cost for the end unit system employed on each RAMA mission. The ranking criteria are on a scale from 1-9, where 9 represents the ideal, lowest cost solutions.

Table 3-12: Total Cost of Manufacturing Method Evaluation Criteria. Each manufacturing method is evaluated over a set of categories that together give a view as to the expected cost level of using such a method with the RAMA architecture.

Categories	Considerations	Ranking
System Size	Does manufacturing method take up a large mass and volume footprint? How does the size of the system constrain the Seed Craft size? What costs does this impose on launch costs for the Seed Craft from Earth?	
Integration Cost	Does the method require significant systems integration or necessitate non-traditional approaches to make operable in space?	
Operations and Support	Does method depend on human in-space operations, tele-robotics, or is it autonomous? Will it have to be constantly operated or monitored, and if so how long does this process last?	
Power Cost	How much power is required for method (normalized for comparison purposes)? Will it require more advanced power generation methods? Will these power methods require their own development program?	
Versatility/Amortization	Is the fabrication system entirely specific to creating one type of asteroid spacecraft? Can the cost of the method be sunk into multiple Seed Craft missions?	
Risk Assessment	What is the probability of success for implementing the method on the first go? If method fails can it be repaired? If it fails can another be launched and work on the same structure? How much money is required to ameliorate risk?	

Shape Error Tolerances

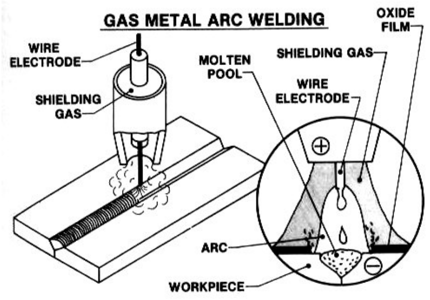
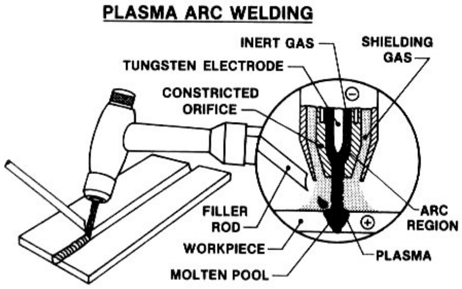
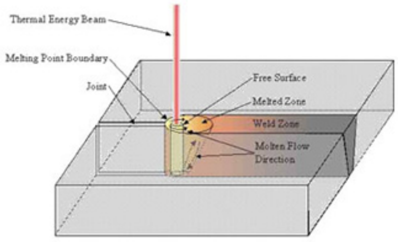
A key performance characteristic of the manufacturing process is the ability to manufacture precise components with little error in the tolerance of the components shape. Therefore, the shape error tolerance metric represents a just worthy criterion for comparing each manufacturing method to one another. The determination of the methods shape error tolerance was based on the following three criteria: An analysis of similar systems and extrapolated from published prototypes, 'back of the envelope' and theoretical calculations, and the methods ability to use feedback control routines to correct the shape errors during manufacturing. The results of this evaluation are presented in expected best-case shape tolerances of the method, as it would be used in the RAMA architecture.

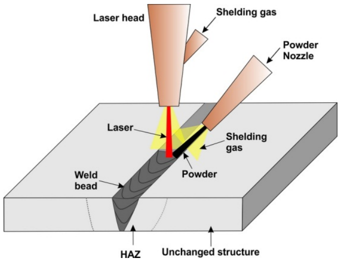
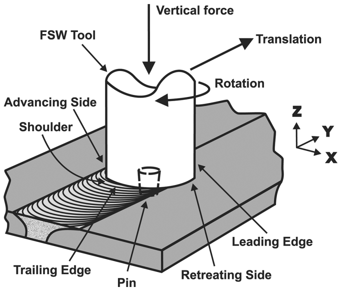
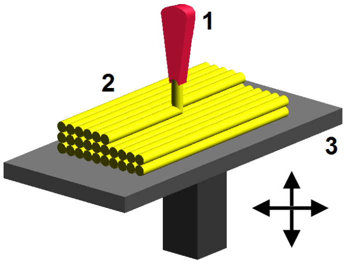
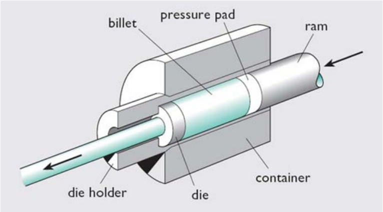
Manufacturing Methods and Analysis

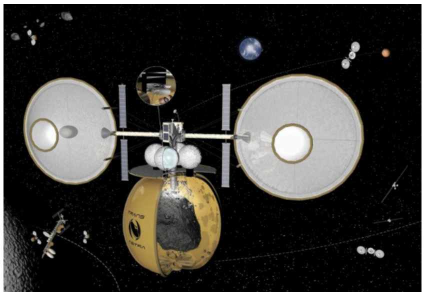
Manufacturing Methods

During the Phase I study the team created a list of manufacturing technologies that hold promise for applicability with the RAMA mission. The technologies selected for analysis all had to be conceivable for potential use within the Seed Craft framework within the anticipated timeframe to first mission commencement. For the most part, the manufacturing technologies studied are additive in nature. Some of which are not solely manufacturing techniques though. In many cases the methods studied are traditionally considered "welding" technologies; but with proper R&D investment could be adapted for additive construction capability with the RAMA architecture. There are other methods that are more subtractive in nature, but still lend well to being used for the desired mission needs. The full list of methods studied is shown in Table 3-13.

Table 3-13: Manufacturing Method Options for In-Situ Construction with the RAMA Architecture

Method	Description	Image/Concept
Gas Metal Arc Welding	Welding process where a consumable wire electrode is fed through the head of torch and joins with the work piece metal through use of an electric arc.	
Plasma Arc Welding	Similar to GTAW, here the electrode is retracted into the torch head, separating the plasma arc from the shield gas and allowing for improvements in arc pressure and temperature.	
Electron Beam Welding	Fuses metals together through use of high velocity electrons. Performed in vacuum. Can be used to weld difficult metals, such as refractory metals and chemically active metals.	

Laser Beam Welding	Welds piece of metal through use of a laser. Useful for high volume applications requiring quality welds. Does not have to be used in vacuum	
Friction Stir Welding	Uses frictional heat from a wear-resistant tool and 2 facing surfaces to generate a solid-state weld. Can also be used to post-process in hybrid processes.	
Extrusion Based Additive Manufacturing	Material is extruded in a molten state from a heated nozzle, then placed in consecutive layers using 3-axis control methods. The part is built up gradually layer-by-layer.	
Laser Engineered Net Shaping	Powder is conveyed through a nozzle using a carrier gas and blown onto a build surface. A laser is then used to melt the deposited layers or the powder.	
Die Extrusion	Material (usually fibers) are driven (pushed or pulled) through a resin bath, cured and extruded from a die to form a structure.	
Regolith/Binder Composite Extrusion	Unprocessed asteroid regolith is combined with a binder and extruded to form a composite structure. The binder may be supplied by the Seed Craft or created in-situ using a synthetic biology process.	

Optical Mining™ /Manufacturing	Previous NIAC work by Joel Sercel, the Optical Mining™ technology is a material processing technique that when deployed with the RAMA architecture may also be used for manufacturing. The method uses concentrated solar light to process asteroid materials into useful constituents.	

Analysis and Comparison

Each manufacturing method described in the previous section was evaluated by the pre-described criteria. The outcome of this evaluation, outlined in Table 3-14, shows which methods hold greatest promise for use in RAMA architectures. It is important to take note that the asteroid applicability column in the table is final determining factor as to which methods can ultimately be used for which asteroid missions. For RAMA missions in which the Seed Craft explores only similar type asteroids, there may be different manufacturing methods used than for RAMA missions in which the Seed Craft will explore a variety of asteroid types. RAMA missions which will explore multiple asteroids of different types creates the most heavily constrained options for manufacturing, or requires a Seed Craft of greater size and complexity capable of carrying multiple manufacturing methods for each asteroid type it encounters.

Table 3-14: Manufacturing Method Comparison and Analysis. Each manufacturing method is ranked here according to the evaluation criteria, showing which methods hold greatest promise for future RAMA use.

Method	TRL	TRL +20	Cost and Potential Success of R&D	Total Cost of Method	Shape Error Tolerances	Asteroid Applicability
Gas Metal Arc Welding	6	9	7	9	~mm	M,S
Plasma Arc Welding	6	9	5	4	~mm	M,S
Electron Beam Welding	6	9	9	5	~mm	M,S
Laser Beam Welding	4	7	3	3	~mm	M,S
Friction Stir Welding	4	7	5	6	~mm	M,S
Extrusion Based Additive Manufacturing	4	9	9	9	0.20 mm	C,M,S
Laser Engineered Net Shaping	4	9	6	8	0.025 mm	M,S
Die Extrusion	3	8	7	6	~mm	C,M,S
Regolith/Binder Composite Extrusion	3	9	8	8	~mm	C,S
Optical Mining/Manufacturing	3	9	10	6	N/A	C,M,S

3.5 S-TYPE ASTEROID MISSION ASSESSMENT

S-type asteroids are the most difficult case for the RAMA system, as they present the tightest constraint on available materials. The problem is one of propellant availability. C-type asteroids contain volatiles which are useful as propellant in a LOX-H2 or thermal water rocket, but S-type asteroids contain almost no water or organics, and the chemical compounds that make up the bulk of their mass are bound up in the form of inert oxides and rocks. This lack of chemical propellant option is partially offset by two advantages:

1) S-type asteroids contain higher proportions of Iron/Nickel, which is useful for local manufacturing and for reinforcing the asteroid.
2) S-type asteroids represent a higher fraction of near earth asteroids, and are generally easier to reach and return from.

Turning an S-type asteroid into a self-propelled spacecraft requires separating the valuable metals, and employing the less valuable silicate rocks as propellant. Due to the chemically inert nature of silicates, the most direct option available would be some form of mechanical propulsion, such as a sling.

Compared to chemical or ion propulsion, the effectiveness of a mechanical system would be limited. Regardless of composition or design, the mass efficiency of any propulsion system is defined exclusively by the exhaust velocity that it is able to produce in its propellant. As mentioned previously, the total ΔV capacity of any propulsion system is purely a function of its exhaust velocity, V_e and the propellant mass fraction of the vehicle, PMF as shown in Equation 4.

$$\Delta \mathrm{V} = -\mathrm{V_e} \cdot \ln(1 - \mathrm{PMF})$$

Equation 4: The Rocket Equation. Propulsion for RAMA is governed by the same principles as any other rocket engine.

Exhaust velocities of 1000-5000 m/s are typical of chemical propulsion, but such performance is impossible for any system that stores its energy mechanically. For any mechanical storage medium (an elastic spring, a flywheel, a tensioned coil etc.) the maximum energy that can be stored by the system without the material yielding is the material’s specific strength, which can be computed as the ratio of yield stress to density σ/ρ. The units of specific strength are $\mathrm{Pa \cdot m3 \cdot kg^{-1}}$ or m^2/s^2, velocity squared. This velocity represents the maximum velocity a mechanical system can theoretically propel itself up to. Figure 3-8 depicts strength vs. densities of materials depicting the point of theoretical mechanical energy stored in different materials for propulsion use cases.

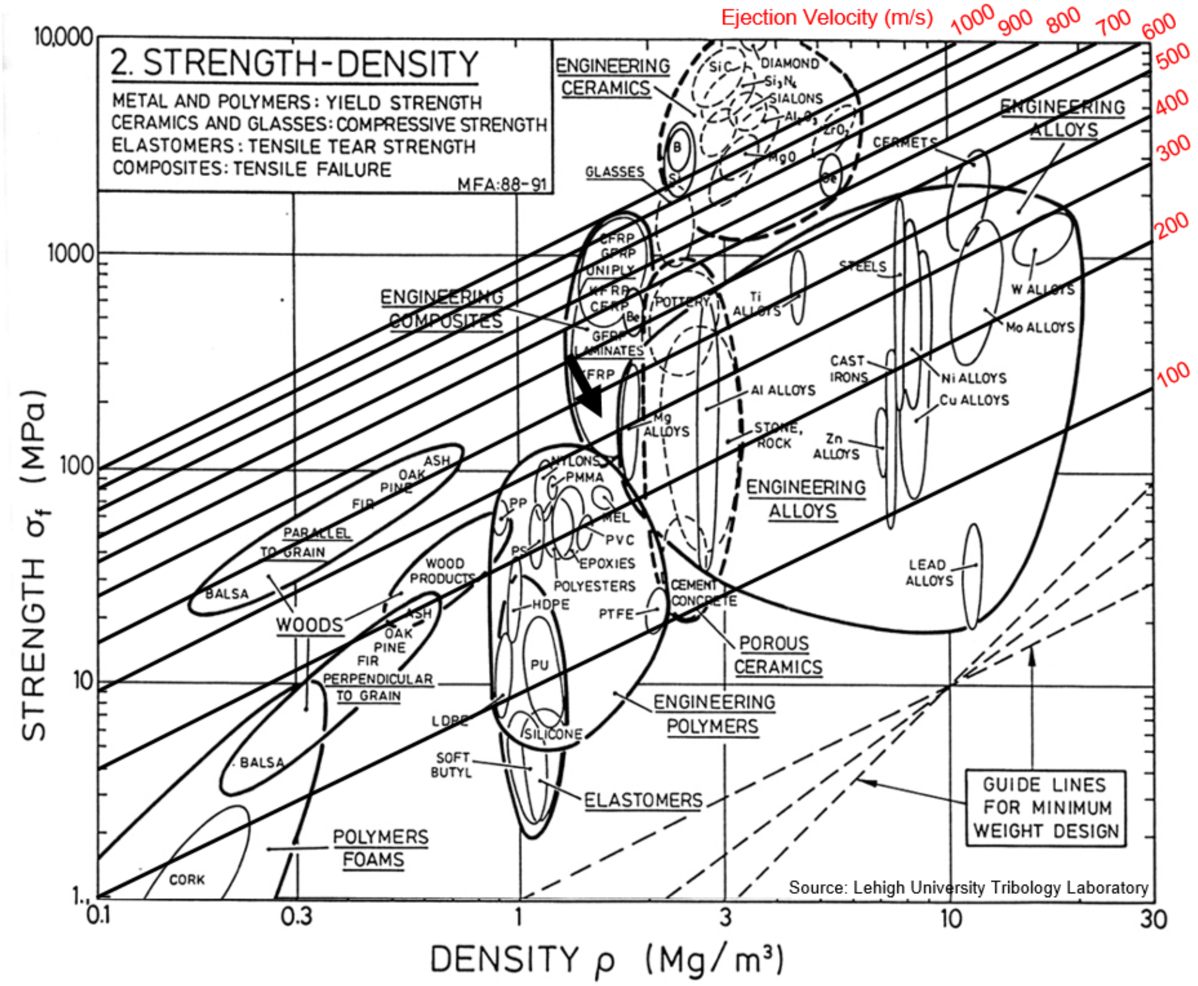


Figure 3-8: Specific Strengths for a range of engineering materials, with values of characteristic velocity shown in red. Note how conventional materials impose limits of 200-500 m/s. Source: Lehigh University Tribology Laboratory

Exotic high strength ceramics with densities of ~3000 kg/m^3 and yield strengths of ~10000 MPa could in theory be used to produce a mechanical propulsion system with exhaust velocities of ~2000 m/s, (corresponding to a specific performance of 205 s, comparable to a low performance mono-prop chemical rocket), but conventional materials available on an S-type asteroid (like stone and iron, even if alloyed to high strength steel) will be limited to a much lower ~500 m/s (I_{sp} ~51 sec).

Reaching these theoretical maximums will also require the propellant to be consumed in small amounts. This further constrains the options available as a large asteroid will take an unacceptable amount of time to break down, mine for materials, and convert into propellant shots. For this study, the technology used to breakdown the asteroid material is assumed to be similar to the Optical Mining technology described in the 2016 NIAC Asteroid Provided In-situ Supplies by Sercel et al. [22] From this study, 10 kW of concentrated sunlight was found to be capable of producing a 1000K spot ~20 cm^2 in area, which was capable of spalling a C-type asteroid analog material into smaller chunks at a rate of 0.7 mm/s. Given the higher heat capacity of stone/metal asteroids, and the 70% higher required operating temperature, it can be estimated that a similar system on an S-type would be capable of spalling asteroid material at a rate of 5.5 mm^3/min per W of applied power. For a system powered by a future 1 MW photovoltaic system, employing high power lasers in place of reflected sunlight, this would produce the ability to decompose the asteroid at a rate of 145 g/sec.

This restriction limits the target selection by size, conversion time and orbit. For a fixed minimum return mass, only targets in similar enough orbits to Earth will have sufficiently low ΔV return values to function with the RAMA system. For a fixed return time, only targets with a small enough initial diameter could be converted in a realistic amount of time. A chart showing multiple examples of NEOs with different diameters, return ΔV value and conversion times are shown in Figure 3-9.

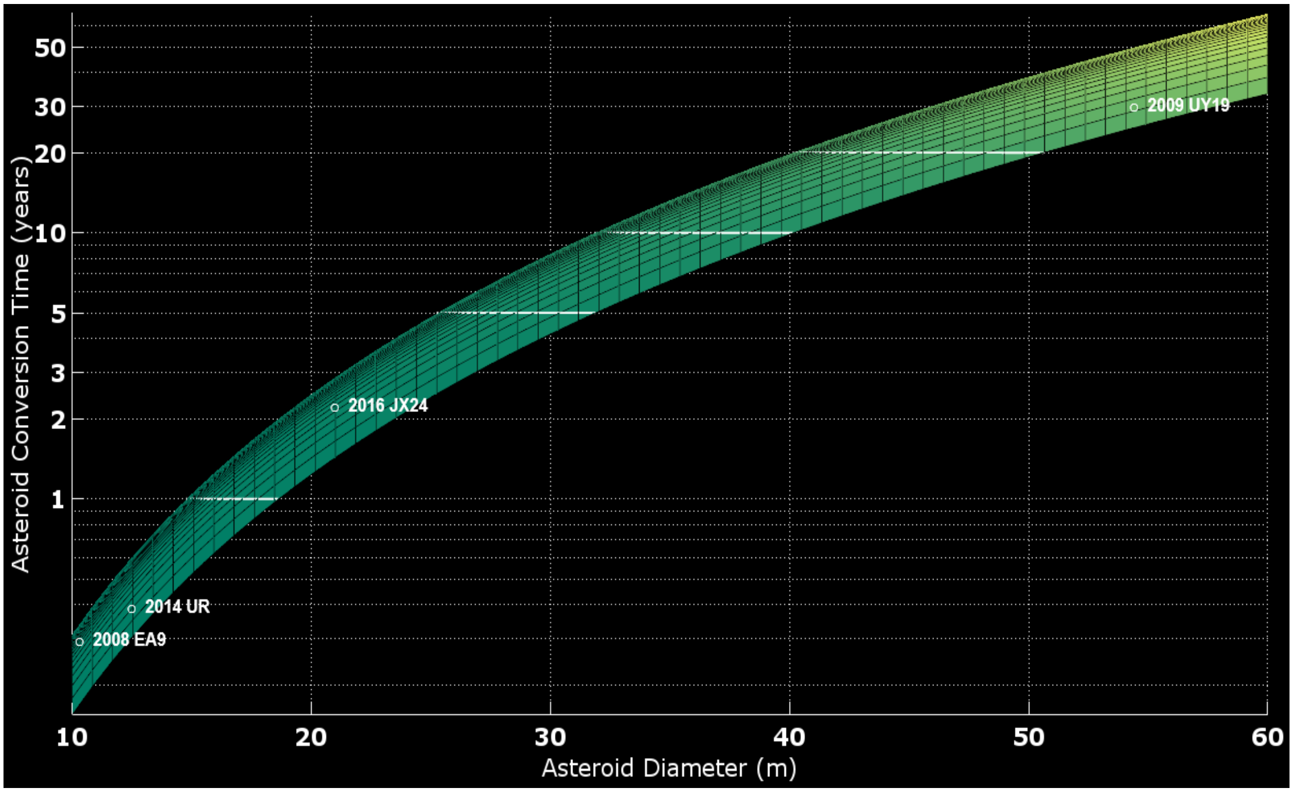


Figure 3-9: Asteroid Conversion Time Vs. Asteroid Diameter. The required conversion time for four NEOs assuming a 1 MW optical mining system, achieving an excavation rate of 145 g/sec. The vertical width of the region represents the range of conversion times a given asteroid may require to produce enough propellant required to affect a 100-500 m/s ΔV for return to Earth (high ΔVs require more propellant to be produced, which requires more of the asteroid to be excavated).

Figure 3-9 shows that a range of mission profiles are possible with S-type asteroids via the RAMA architecture. A RAMA spacecraft with the return capability of the ARM mission can be produced in less than a year, a more ambitious 20m spacecraft can be produced in 2 years, and an extremely long term project could be undertaken to convert an asteroid like 2009 UY19 (shown in the upper right corner of the chart), returning >10,000 metric-tonnes of material to cislunar space over the course of a 30 year mission. While such a timeline may seem too long, it represents the equivalent of returning the mass of the ISS in resources to Earth orbit every year for 30 years. Because it is the most ambitious and far reaching case, it is the case we studied in more detail for this Phase I study.

3.5.1 THE FAR END OF THE SPECTRUM – ASTEROID 2009 UY19

We chose to study in depth a known asteroid that exists at the far end of the “feasibility spectrum” in an effort to show the true possibility of the RAMA architecture. Asteroid 2009 UY19 is an S-type asteroid with an estimated diameter of 50-150m. Part of what makes this a far end of the spectrum asteroid to study is the conversion time needed to convert it into an asteroid spacecraft. Shown in detail within this section, UY19 will require nearly a decade of Seed Craft conversion in-situ to be ready for its mission to Earth-Moon L5. This conversion rate is based on modest assumptions of Seed Craft functionality, which in due time may improve significantly, thus decreasing conversion time. Nonetheless, the study of this large of an asteroid, and the feasibility analysis of doing so, outlines the true disruptive capability of the RAMA architecture.

The asteroid 2009 UY19 was discovered during a close flyby of Earth in October 2009, and makes periodic close passes of the Earth every 29 years. During these passes, it comes within a few million km (~10 Lunar Distances) of Earth, and the next pass in 2039 requires a ΔV of only 437 m/s to be diverted towards the Earth-Moon L5 point. This makes it an attractive target for returning to cislunar space for resource extraction. It is too massive to be recovered by any proposed ARM architecture, but it is a prime target for the RAMA concept. The orbital parameters of 2009 UY19 are shown in Table 3-15.

Table 3-15: Orbital Parameters of 2009 UY19

2009 UY19 Asteroid Orbit		
Semi-major axis	1.02361	AU
Eccentricity	0.030796	-
Inclination	9.05	deg
Period	1.036	years
Synodic Period	29.07	years

Even for a NEO, the orbit of UY19 is very similar to Earth, the only significant difference being its relatively high inclination to the plane of the ecliptic. The relative orbits and trajectory recommended by NHATS is shown in Figure 3-10 centered on Earth.

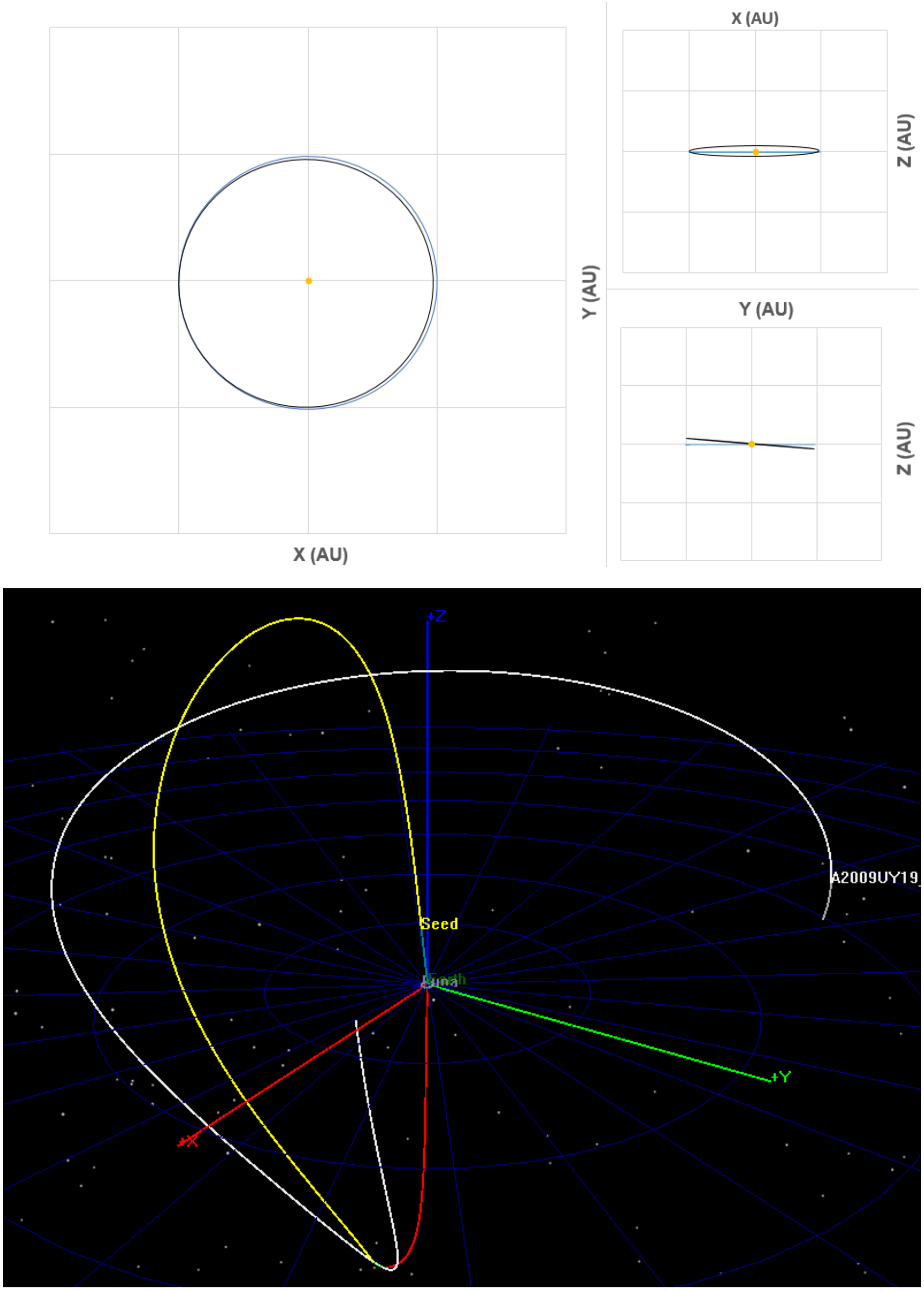


Figure 3-10: The trajectory of 2009 UY19 as recommended by NHATS, and computed in the General Mission Assessment Tool (GMAT). The coordinates in the upper figure are sun centered, while the lower figure are Earth centered, with the orbit of the moon shown in grey for scale. The Seed craft follows the red trajectory away from Earth and out of the plane of the ecliptic, rendezvousing with the asteroid (shown in white), remaining there for 8 days, then returning along the yellow trajectory. The 2039 trajectory is especially favorable, but options like this occur once every synodic period (every 29 years). If the Seed craft remains on the asteroid for 8 days plus one synodic period, an equally favorable Earth return window opens at its conclusion.

Like most NEOs, UY19 has never been resolved by any telescope, and spectral data has never been taken to reveal its composition, but its apparent magnitude and proximity to Earth indicate it is most likely an S-type with a diameter of 36-163 m. Detailed information on its size and composition would need to be collected by a remote sensing campaign before any RAMA concept vehicle was launched, but for the purposes of this study, the following assumptions in Table 3-16 were made about UY19.

Table 3-16: The assumed properties of 2009 UY19 assumed in this study. Assumptions represent the approximate middle of possible range of values. Source: http://neo.jpl.nasa.gov/

2009 UY19 Assumed Physical Properties	
Type	S
Albedo	0.26
Diameter (m)	54
Mass (kg)	2.3E+08
Volume (m^3)	8.5E+04
Density (kg/m^3)	2700

With the physical dimensions of the asteroid fixed, it is possible to estimate the materials available at the asteroid for constructing the RAMA spacecraft components. Under the standard composition model assumed by Rock Finder, the composition breakdown for UY19 is shown in Table 3-17.

Table 3-17: Mass budget of UY19, broken down by component

Available Materials						
	Density (kg/m^3)	Mass (kg)	Volume (m^3)	Mass Fraction	Volume Fraction	Diameter Equivalent* (m)
Rock, Olivine $(Mg,Fe)_2SiO_4$	3320	9.47E+07	2.85E+04	42%	33.75%	38
Rock, Orthopyroxene $(Mg,Fe)_2Si_2O_6$	3200	8.26E+07	2.58E+04	36%	30.54%	37
Iron	7874	3.42E+07	4.35E+03	15%	5.14%	20
Nickel	8908	1.67E+07	1.87E+03	7%	2.21%	15
Total	2700	2.28E+08	8.5E+04	100%	100%	54

*The equivalent diameter of the component if collected into a single mass

This composition illustrates why **stony/iron asteroids present the greatest challenge to the RAMA architecture**: They provide very few materials to work with. There is effectively no water or volatiles to produce propellant for chemical engines, and most of the mass is bound up in inert oxides and rocks. The result of these limitations can be illustrated in the Figure 3-11 where the overall ISRU process shown in section 3.3.4 is minimized based on available materials and manufacturing capabilities.

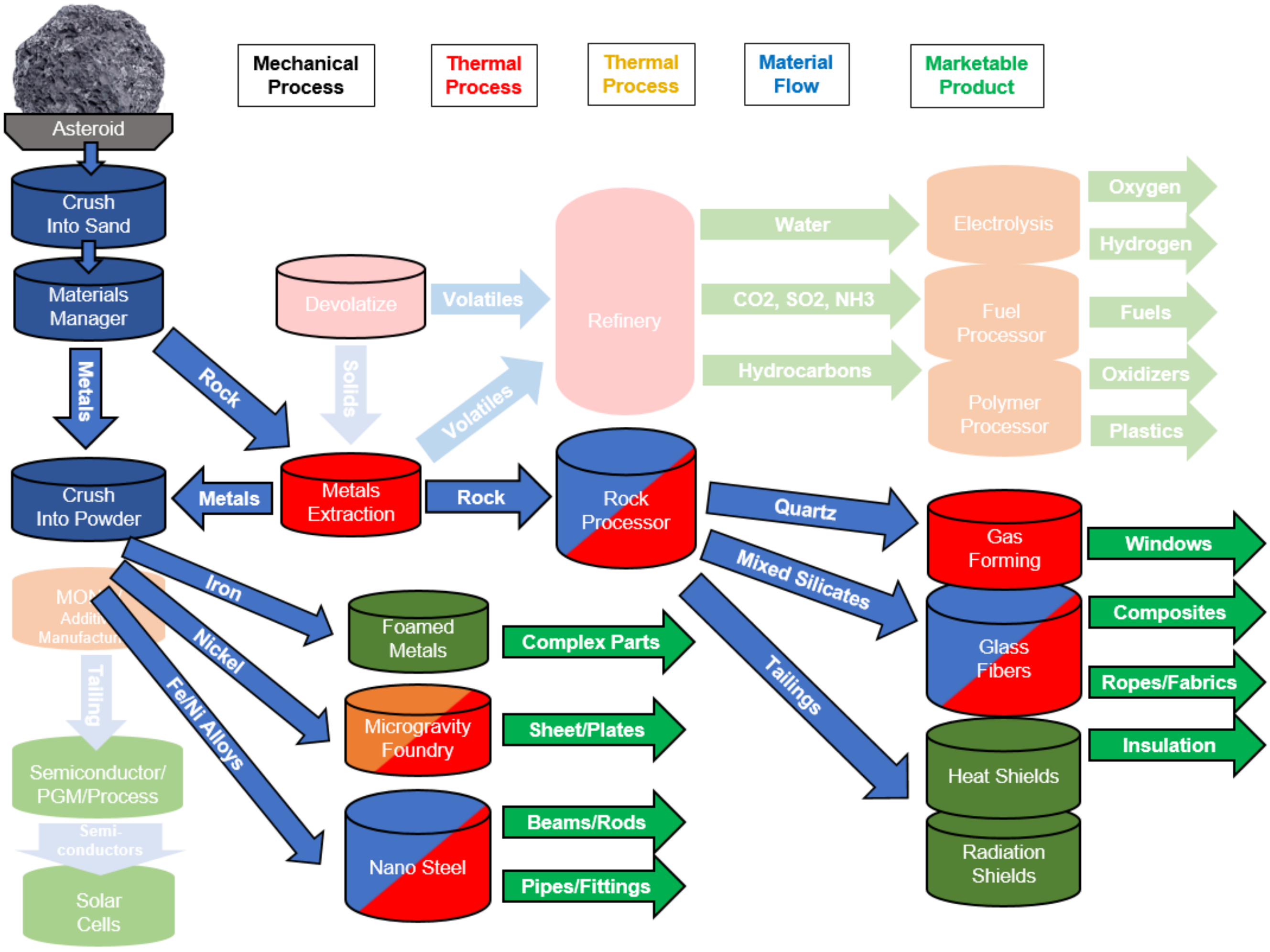
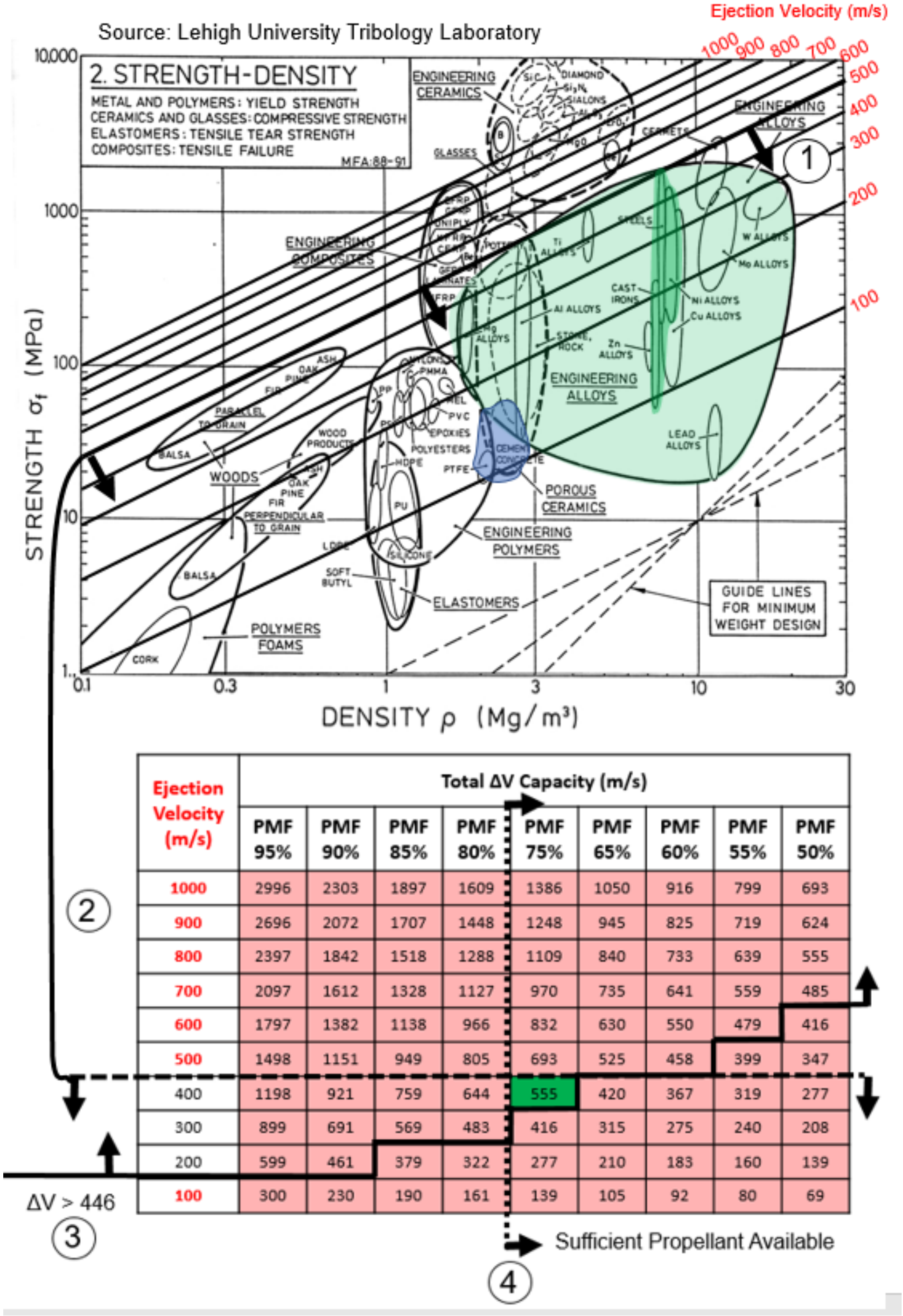


Figure 3-11: Tuning the ISRU Process for S-Type RAMA Architecture

When presented with an S-type asteroid like UY19, RAMA is forced to make use of mechanical methods of propulsion. The mass efficiency of a propulsion system is defined entirely by the exhaust velocity it produces, and the low energy density of mechanical components means mechanical propulsion will be restricted to comparatively low exhaust velocities. In fact, it is possible to constrain the theoretical upper limit of any purely mechanical propulsion system based only on the materials it is made from.

How this limitation impacts target selection and propulsion system design is illustrated in Figure 3-12. The ΔV required to return the asteroid to Earth is fixed by the asteroid's orbit. By selecting a material to construct the propulsion system from, the maximum ejection velocity is constrained. This allows the required propellant consumption to be computed across the range of possible ejection velocities. By selecting a secondary material to serve as the propellant (in this case, inert rock) the amount of propellant available can also be constrained. Only targets that satisfy these four constraints can be returned by a fully mechanical RAMA system.



Ejection Velocity (m/s)	Total ΔV Capacity (m/s)								
	PMF 95%	PMF 90%	PMF 85%	PMF 80%	PMF 75%	PMF 65%	PMF 60%	PMF 55%	PMF 50%
1000	2996	2303	1897	1609	1386	1050	916	799	693
900	2696	2072	1707	1448	1248	945	825	719	624
800	2397	1842	1518	1288	1109	840	733	639	555
700	2097	1612	1328	1127	970	735	641	559	485
600	1797	1382	1138	966	832	630	550	479	416
500	1498	1151	949	805	693	525	458	399	347
400	1198	921	759	644	555	420	367	319	277
300	899	691	569	483	416	315	275	240	208
200	599	461	379	322	277	210	183	160	139
100	300	230	190	161	139	105	92	80	69

Figure 3-12: A representation of the constrained optimization process for Asteroid 2009 UY19. Beginning with the assumed asteroid type and available materials, 1) The maximum ejection velocity of the propulsion system can be estimated. 2) This constrains the maximum performance of the propulsion system at all propellant mass fraction (PMF) values. 3) The required total ΔV of the system to return the asteroid to Earth is constrained by values from NHATS (if available) or estimated from the asteroid's orbital elements. 4) The selection of propellant material on the asteroid limits the amount of propellant available, and constrains the PMF. Only on asteroids where all 4 of the above constraints can be met would the RAMA spacecraft be capable of completing its mission.

Seed Craft Loadout

With no known sources of volatiles at UY19, the Seed Craft is customized for metal working and stone mining. No chemical processing equipment is included; instead the Seed Craft is loaded with four modules containing the following equipment:

1) Optical mining rig, containing a bank of one hundred 10kW lasers and a collection inlet, capable of spalling and collecting asteroid material at a rate of ~.5 kg/s.

2) 5kW furnace for smelting and electromagnetically separating iron/nickel from rock.

3) 5000 kg of alloying elements and equipment for producing high strength steel.

4) A die extruder for extruding high strength steel into a circular beam 16 cm in diameter.

5) A 750 kg electromagnetic bearing assembly for permanent installation on the asteroid.

The mission was designed by taking into account the closest approach windows for UY19 and then backing out each stage of the mission based on time from launch estimates. The timeline is shown in Table 3-18.

Table 3-18: 2009 UY19 RAMA Mission Timeline

Seed Craft	UY19/RAMA	Date
Earth Departure		T+0.0 yrs
	Earth Closest Approach	T+0.0 yrs
NEO Intercept Burn Begins		T+0.25 yrs
NEO Intercept Burn Completes Arrives at Target		T+0.30 yrs
Docking	Docking	T+0.32 yrs
Construction Begins	Excavation, surface smoothing, reinforcement	T+0.40 yrs
	Construction Complete	T+8.40 yrs
	Propulsion Charge Up Begins	T+29.0 yrs
Depart RAMA	Propulsion Charge Up Complete	T+29.16 yrs
	Earth Orbital Intercept Maneuver Begins	T+29.16 yrs
	Earth Orbital Intercept Maneuver Complete	T+29.41 yrs
	Earth Arrival	T+30.0 yrs

UY19 Mission Timeline

The Seed Craft is boosted away from its base in cislunar space on a trajectory to intercept the asteroid. It ignites its 60-kW solar electric propulsion system 4 months later, affecting a rendezvous with UY19 0.32 years after launch. After 2-4 days orbiting the asteroid and mapping details of its mass distribution and gravity, it docks with UY19 along the asteroid's spin axis, and anchors itself to the surface. The Seed Craft is now effectively part of the asteroid, and continues with it out of cislunar space. The Seed Craft then reconfigures itself for operations on the asteroid, deploying a group of independent robots to assist with securing the Seed Craft, removing obstructions, and any precision work that is required during the process. The full capacity of the Seed Craft's four 27x34m solar arrays is deployed, providing the full 4 MW of solar power required to convert the asteroid into the RAMA spacecraft.

With its assumed composition and size, gravity at the asteroid's surface is only .00002 g's (~2 um/s^2). The asteroid is thus likely to be a single monolithic piece, as any loosely bound components would have escaped the asteroid long ago. The lack of gravity and the cohesive nature of the asteroid will make mechanical excavation very difficult. Optical mining methods have been previously studied as ways of overcoming both difficulties in mining C-type asteroid by Sercel et al. [22] With a 10kW Optical Mining system operating at a temperature of 1000K, an excavation rate of ~5 mm^3/min of material per W of power was observed (Figure 3-13). By directing the full power of the Seed Craft's solar array to the optical mining system and operating at the higher temperature required to decompose stone and metal, an excavation rate of ~200 cm^3/s can be expected.

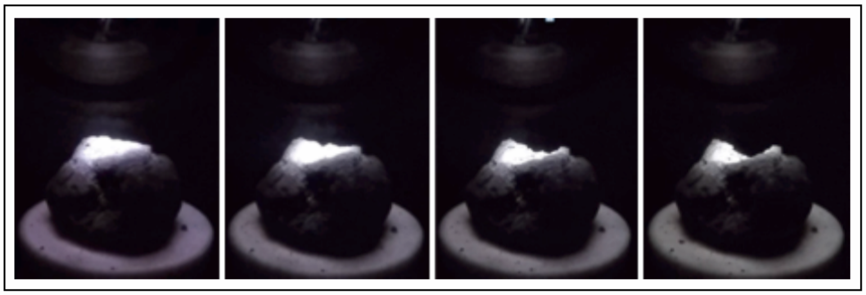


Figure 3-13: Optical Mining Example (source: Sercel et al.)

The resulting debris from the mining site are lost to space until the Seed craft has bored a hole deep enough to insert the mining module into the asteroid, forming a closed cavity to prevent the loss of more debris. The material is then directed to an inlet adjacent to the optimal mining rig, where it is collected and conveyed away from the mining site to be purified and smelted.

The melted rock is allowed to cool in measured batches ("shots") 18 cm in diameter. By cooling them in the presence of an electromagnetic field, they are left with a remnant magnetic field that makes them cohere to each other magnetically, and to the walls of the asteroid. These 18 cm shots will be used as the propellant for the mechanical propulsive system, and are packed around the wall of the ever-growing interior of the asteroid.

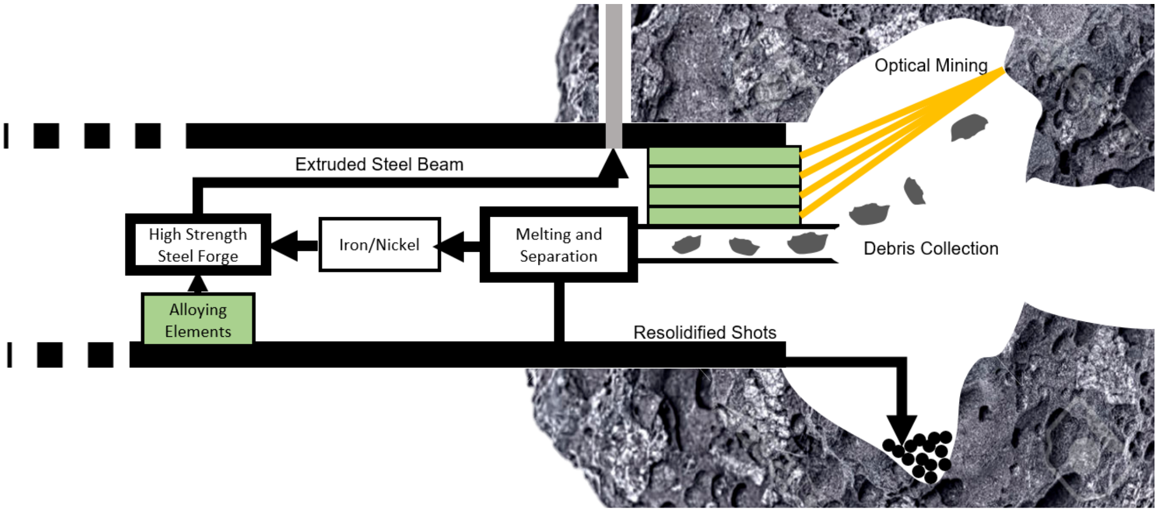


Figure 3-14: Schematic of the RAMA conversion process. The schematic shows the inside elements of the Seed Craft while manufacturing on the asteroid.

The process of optically hollowing out the interior of the UY19 takes 8 years, producing a new shot every 17 seconds. Figure 3-15 shows the concept of the Seed Craft conversion of UY19 into the asteroid spacecraft, and Figure 3-14 shows a more detailed depiction of the Seed Craft operations on the asteroid. For the first decade of this process, a small fraction of the iron and nickel extracted from the material is not returned to the interior of the asteroid or embedded in the shots, but is separated and combined with the carbon and other alloying elements from the Seed craft to produce high strength steel. The steel is extruded through a die out through radial bore holes in the asteroid excavated by the robots until it extends 40 m in length.

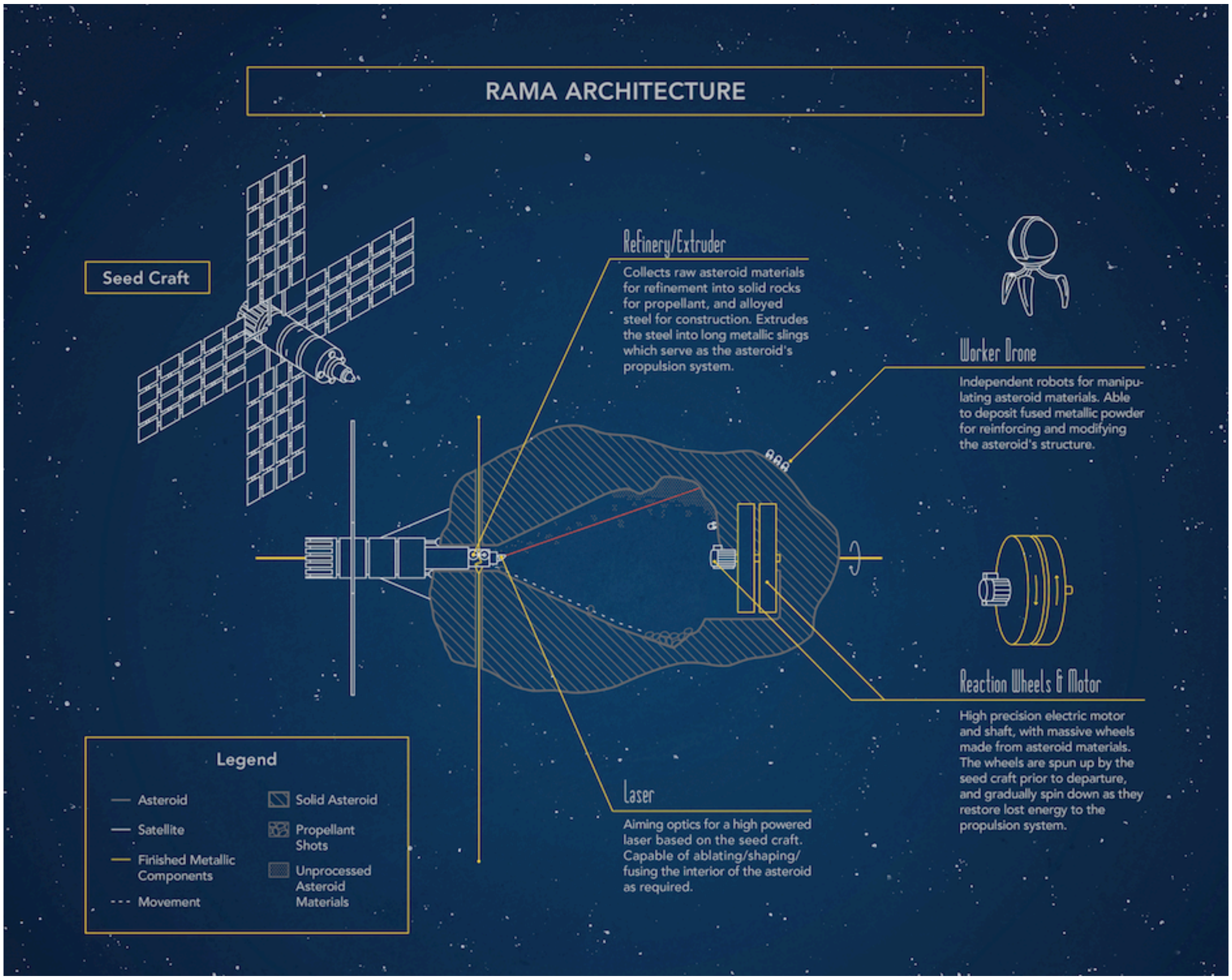
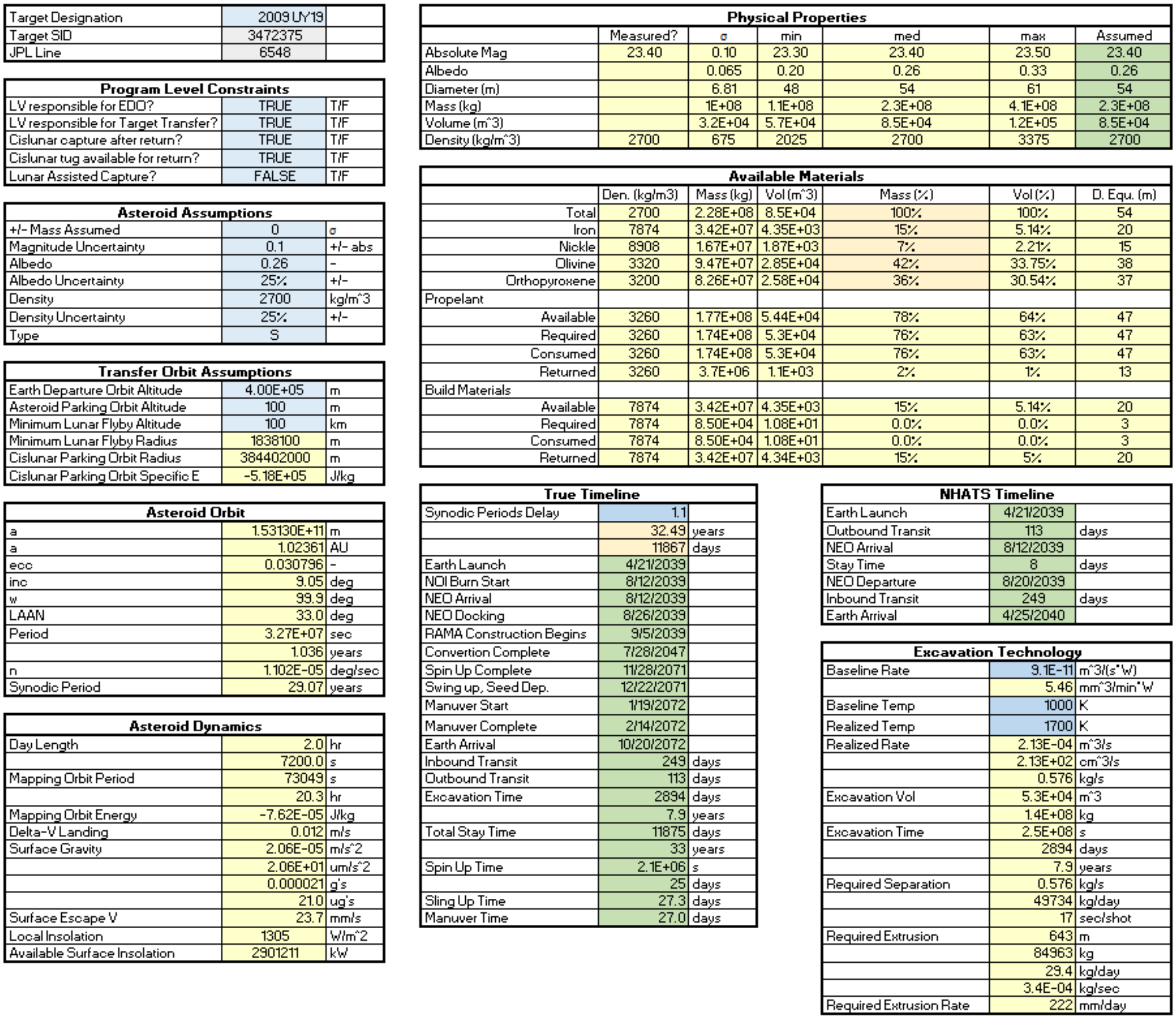


Figure 3-15: The RAMA Architecture for the S-type asteroid 2009 UY19.

These "slings" are used for the main component of RAMA's propulsion system. Rock Finder is capable of computing the sling performance characteristics and sizing as shown in Figure 3-16, Figure 3-17 and Figure 3-18. The base of each sling is firmly anchored to the interior of the asteroid. A series of 16 slings are extruded at equally spaced intervals around the asteroid. While the amount of material consumed in their production is large, (300 mT of materials to produce 80 mT of metal) it is small compared to the amount of material required to produce the shots. The minimal ability to extrude 29 kg (220 mm of beams) per day would take less than a year to finish. After that, metal is available to reinforce the interior of the asteroid, provide scaffolding for the robots, or reduced into a powder for joining and reinforcement via laser engineered net shaping with the mining lasers.



Target Designation	2009 UY19	
Target SID	3472375	
JPL Line	6548	

Program Level Constraints

LV responsible for EDO?	TRUE	T/F
LV responsible for Target Transfer?	TRUE	T/F
Cislunar capture after return?	TRUE	T/F
Cislunar tug available for return?	TRUE	T/F
Lunar Assisted Capture?	FALSE	T/F

Asteroid Assumptions

+/- Mass Assumed	0	σ
Magnitude Uncertainty	0.1	+/- abs
Albedo	0.26	-
Albedo Uncertainty	25%	+/-
Density	2700	kg/m^3
Density Uncertainty	25%	+/-
Type	S	

Transfer Orbit Assumptions

Earth Departure Orbit Altitude	4.00E+05	m
Asteroid Parking Orbit Altitude	100	m
Minimum Lunar Flyby Altitude	100	km
Minimum Lunar Flyby Radius	1838100	m
Cislunar Parking Orbit Radius	384402000	m
Cislunar Parking Orbit Specific E	-5.18E+05	J/kg

Asteroid Orbit

a	1.53130E+11	m
a	1.02361	AU
ecc	0.030796	-
inc	9.05	deg
w	99.9	deg
LAAN	33.0	deg
Period	3.27E+07	sec
	1.036	years
n	1.102E-05	deg/sec
Synodic Period	29.07	years

Asteroid Dynamics

Day Length	2.0	hr
	7200.0	s
Mapping Orbit Period	73049	s
	20.3	hr
Mapping Orbit Energy	-7.62E-05	J/kg
Delta-V Landing	0.012	m/s
Surface Gravity	2.06E-05	m/s^2
	2.06E+01	um/s^2
	0.000021	g's
	21.0	ug's
Surface Escape V	23.7	mm/s
Local Insolation	1305	W/m^2
Available Surface Insolation	2901211	kW

Physical Properties

	Measured?	σ	min	med	max	Assumed
Absolute Mag	23.40	0.10	23.30	23.40	23.50	23.40
Albedo		0.065	0.20	0.26	0.33	0.26
Diameter (m)		6.81	48	54	61	54
Mass (kg)		1E+08	1.1E+08	2.3E+08	4.1E+08	2.3E+08
Volume (m^3)		3.2E+04	5.7E+04	8.5E+04	1.2E+05	8.5E+04
Density (kg/m^3)	2700	675	2025	2700	3375	2700

Available Materials

	Den. (kg/m3)	Mass (kg)	Vol (m^3)	Mass (%)	Vol (%)	D. Equ. (m)
Total	2700	2.28E+08	8.5E+04	100%	100%	54
Iron	7874	3.42E+07	4.35E+03	15%	5.14%	20
Nickle	8908	1.67E+07	1.87E+03	7%	2.21%	15
Olivine	3320	9.47E+07	2.85E+04	42%	33.75%	38
Orthopyroxene	3200	8.26E+07	2.58E+04	36%	30.54%	37
Propelant						
Available	3260	1.77E+08	5.44E+04	78%	64%	47
Required	3260	1.74E+08	5.3E+04	76%	63%	47
Consumed	3260	1.74E+08	5.3E+04	76%	63%	47
Returned	3260	3.7E+06	1.1E+03	2%	1%	13
Build Materials						
Available	7874	3.42E+07	4.35E+03	15%	5.14%	20
Required	7874	8.50E+04	1.08E+01	0.0%	0.0%	3
Consumed	7874	8.50E+04	1.08E+01	0.0%	0.0%	3
Returned	7874	3.42E+07	4.34E+03	15%	5%	20

True Timeline

Synodic Periods Delay	1.1	
	32.49	years
	11867	days
Earth Launch	4/21/2039	
NOI Burn Start	8/12/2039	
NEO Arrival	8/12/2039	
NEO Docking	8/26/2039	
RAMA Construction Begins	9/5/2039	
Convertion Complete	7/28/2047	
Spin Up Complete	11/28/2071	
Swing up, Seed Dep.	12/22/2071	
Manuver Start	1/19/2072	
Manuver Complete	2/14/2072	
Earth Arrival	10/20/2072	
Inbound Transit	249	days
Outbound Transit	113	days
Excavation Time	2894	days
	7.9	years
Total Stay Time	11875	days
	33	years
Spin Up Time	2.1E+06	s
	25	days
Sling Up Time	27.3	days
Manuver Time	27.0	days

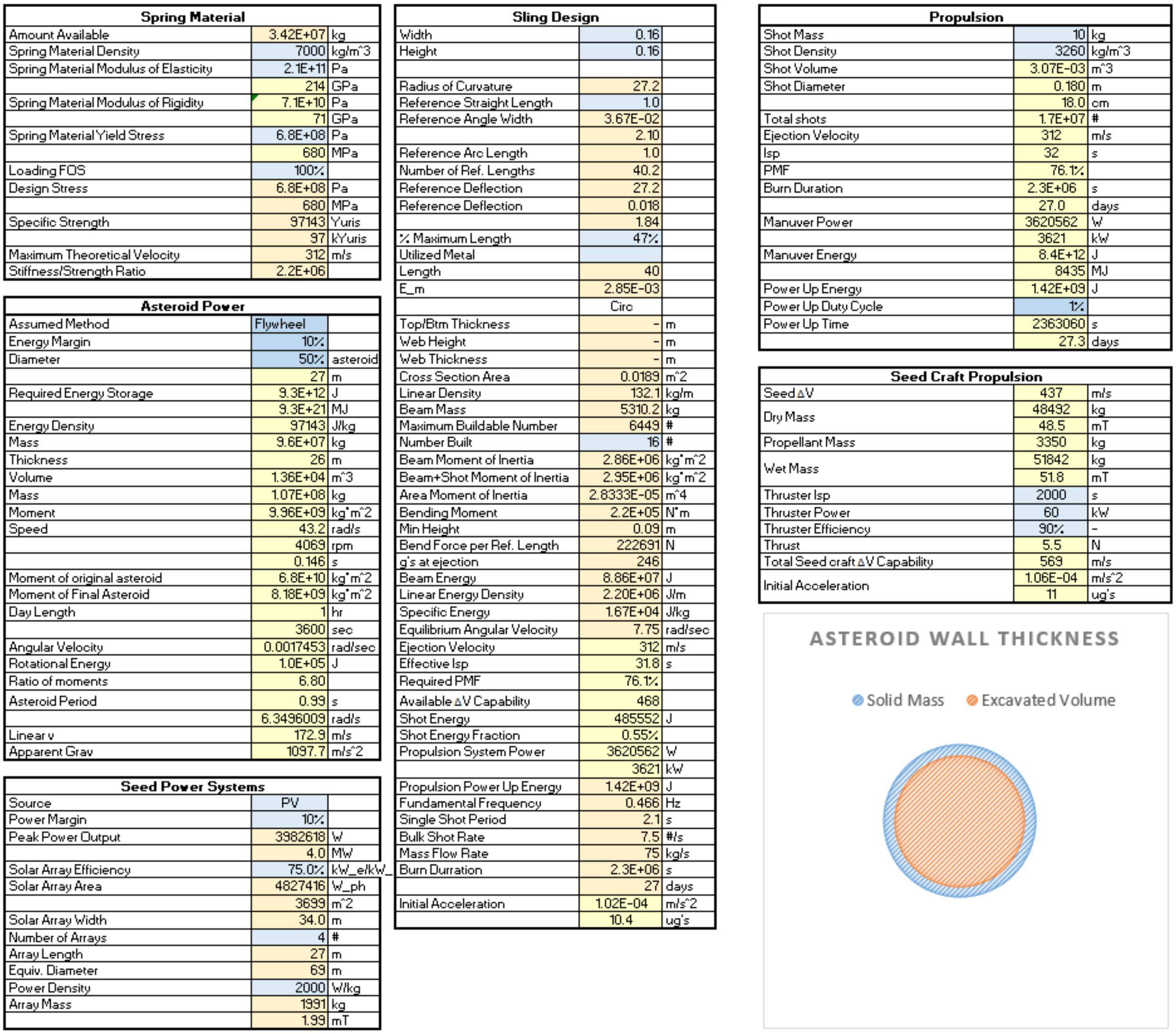
NHATS Timeline

Earth Launch	4/21/2039	
Outbound Transit	113	days
NEO Arrival	8/12/2039	
Stay Time	8	days
NEO Departure	8/20/2039	
Inbound Transit	249	days
Earth Arrival	4/25/2040	

Excavation Technology

Baseline Rate	9.1E-11	m^3/(s*W)
	5.46	mm^3/min*W
Baseline Temp	1000	K
Realized Temp	1700	K
Realized Rate	2.13E-04	m^3/s
	2.13E+02	cm^3/s
	0.576	kg/s
Excavation Vol	5.3E+04	m^3
	1.4E+08	kg
Excavation Time	2.5E+08	s
	2894	days
	7.9	years
Required Separation	0.576	kg/s
	49734	kg/day
	17	sec/shot
Required Extrusion	643	m
	84963	kg
	29.4	kg/day
	3.4E-04	kg/sec
Required Extrusion Rate	222	mm/day

Figure 3-16: Part 1 of 3 of the Rock Finder front end for 2009UY19. Shown are the top level inputs (top left) for the mission, the asteroid calculated properties and materials budget (top right), the asteroids calculated orbital and dynamic properties (bottom left) and the overall timeline (bottom middle). Also shown are the calculated requirements for the system used to excavate the asteroid in order to meet the required timeline. All values shown in yellow are automatically calculated and update/imported immediately in response to new user specified inputs.



Spring Material		
Amount Available	3.42E+07	kg
Spring Material Density	7000	kg/m^3
Spring Material Modulus of Elasticity	2.1E+11	Pa
	214	GPa
Spring Material Modulus of Rigidity	7.1E+10	Pa
	71	GPa
Spring Material Yield Stress	6.8E+08	Pa
	680	MPa
Loading FOS	100%	
Design Stress	6.8E+08	Pa
	680	MPa
Specific Strength	97143	Yuris
	97	kYuris
Maximum Theoretical Velocity	312	m/s
Stiffness/Strength Ratio	2.2E+06	

Asteroid Power		
Assumed Method	Flywheel	
Energy Margin	10%	
Diameter	50%	asteroid
	27	m
Required Energy Storage	9.3E+12	J
	9.3E+21	MJ
Energy Density	97143	J/kg
Mass	9.6E+07	kg
Thickness	26	m
Volume	1.36E+04	m^3
Mass	1.07E+08	kg
Moment	9.96E+09	kg*m^2
Speed	43.2	rad/s
	4069	rpm
	0.146	s
Moment of original asteroid	6.8E+10	kg*m^2
Moment of Final Asteroid	8.18E+09	kg*m^2
Day Length	1	hr
	3600	sec
Angular Velocity	0.0017453	rad/sec
Rotational Energy	1.0E+05	J
Ratio of moments	6.80	
Asteroid Period	0.99	s
	6.3496009	rad/s
Linear v	172.9	m/s
Apparent Grav	1097.7	m/s^2

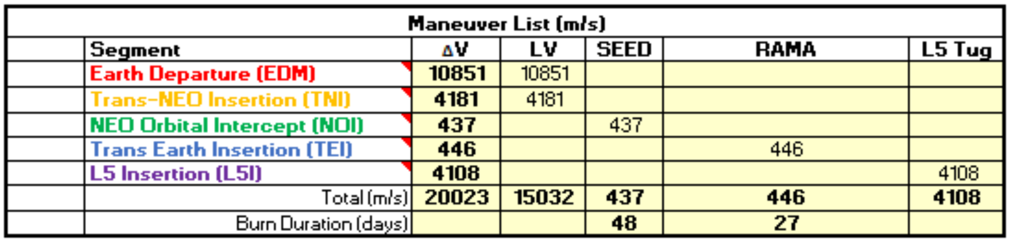
Seed Power Systems		
Source	PV	
Power Margin	10%	
Peak Power Output	3982618	W
	4.0	MW
Solar Array Efficiency	75.0%	kW_e/kW_
Solar Array Area	4827416	W_ph
	3699	m^2
Solar Array Width	34.0	m
Number of Arrays	4	#
Array Length	27	m
Equiv. Diameter	69	m
Power Density	2000	W/kg
Array Mass	1991	kg
	1.99	mT

Sling Design		
Width	0.16	
Height	0.16	
Radius of Curvature	27.2	
Reference Straight Length	1.0	
Reference Angle Width	3.67E-02	
	2.10	
Reference Arc Length	1.0	
Number of Ref. Lengths	40.2	
Reference Deflection	27.2	
Reference Deflection	0.018	
	1.84	
% Maximum Length	47%	
Utilized Metal		
Length	40	
E_m	2.85E-03	
	Circ	
Top/Btm Thickness	-	m
Web Height	-	m
Web Thickness	-	m
Cross Section Area	0.0189	m^2
Linear Density	132.1	kg/m
Beam Mass	5310.2	kg
Maximum Buildable Number	6449	#
Number Built	16	#
Beam Moment of Inertia	2.86E+06	kg*m^2
Beam+Shot Moment of Inertia	2.95E+06	kg*m^2
Area Moment of Inertia	2.8333E-05	m^4
Bending Moment	2.2E+05	N*m
Min Height	0.09	m
Bend Force per Ref. Length	222691	N
g's at ejection	246	
Beam Energy	8.86E+07	J
Linear Energy Density	2.20E+06	J/m
Specific Energy	1.67E+04	J/kg
Equilibrium Angular Velocity	7.75	rad/sec
Ejection Velocity	312	m/s
Effective Isp	31.8	s
Required PMF	76.1%	
Available ΔV Capability	468	
Shot Energy	485552	J
Shot Energy Fraction	0.55%	
Propulsion System Power	3620562	W
	3621	kW
Propulsion Power Up Energy	1.42E+09	J
Fundamental Frequency	0.466	Hz
Single Shot Period	2.1	s
Bulk Shot Rate	7.5	#/s
Mass Flow Rate	75	kg/s
Burn Durration	2.3E+06	s
	27	days
Initial Acceleration	1.02E-04	m/s^2
	10.4	ug's

Propulsion		
Shot Mass	10	kg
Shot Density	3260	kg/m^3
Shot Volume	3.07E-03	m^3
Shot Diameter	0.180	m
	18.0	cm
Total shots	1.7E+07	#
Ejection Velocity	312	m/s
Isp	32	s
PMF	76.1%	
Burn Duration	2.3E+06	s
	27.0	days
Manuver Power	3620562	W
	3621	kW
Manuver Energy	8.4E+12	J
	8435	MJ
Power Up Energy	1.42E+09	J
Power Up Duty Cycle	1%	
Power Up Time	2363060	s
	27.3	days

Seed Craft Propulsion		
Seed ΔV	437	m/s
Dry Mass	48492	kg
	48.5	mT
Propellant Mass	3350	kg
Wet Mass	51842	kg
	51.8	mT
Thruster Isp	2000	s
Thruster Power	60	kW
Thruster Efficiency	90%	-
Thrust	5.5	N
Total Seed craft ΔV Capability	569	m/s
Initial Acceleration	1.06E-04	m/s^2
	11	ug's

Figure 3-17: Part 2 of 3 of the Rock Finder front end for 2009UY19. Shown are the user specified assumption about the primary structural material mined from the asteroid and used to construct the energy storage system (middle left) and the propulsion slings (top middle). The summarized propulsion calculations for both the Seed Craft and the RAMA craft are shown on the right. As in part 1, only the values shown in blue require specification by the user, and the optimal values for each remaining value (in yellow) are automatically computed and presented for rapid evaluation.



	Maneuver List (m/s)					
	Segment	**ΔV**	**LV**	**SEED**	**RAMA**	**L5 Tug**
	Earth Departure (EDM)	**10851**	10851			
	Trans-NEO Insertion (TNI)	**4181**	4181			
	NEO Orbital Intercept (NOI)	**437**		437		
	Trans Earth Insertion (TEI)	**446**			446	
	L5 Insertion (L5I)	**4108**				4108
	Total (m/s)	**20023**	**15032**	**437**	**446**	**4108**
	Burn Duration (days)			**48**	**27**	

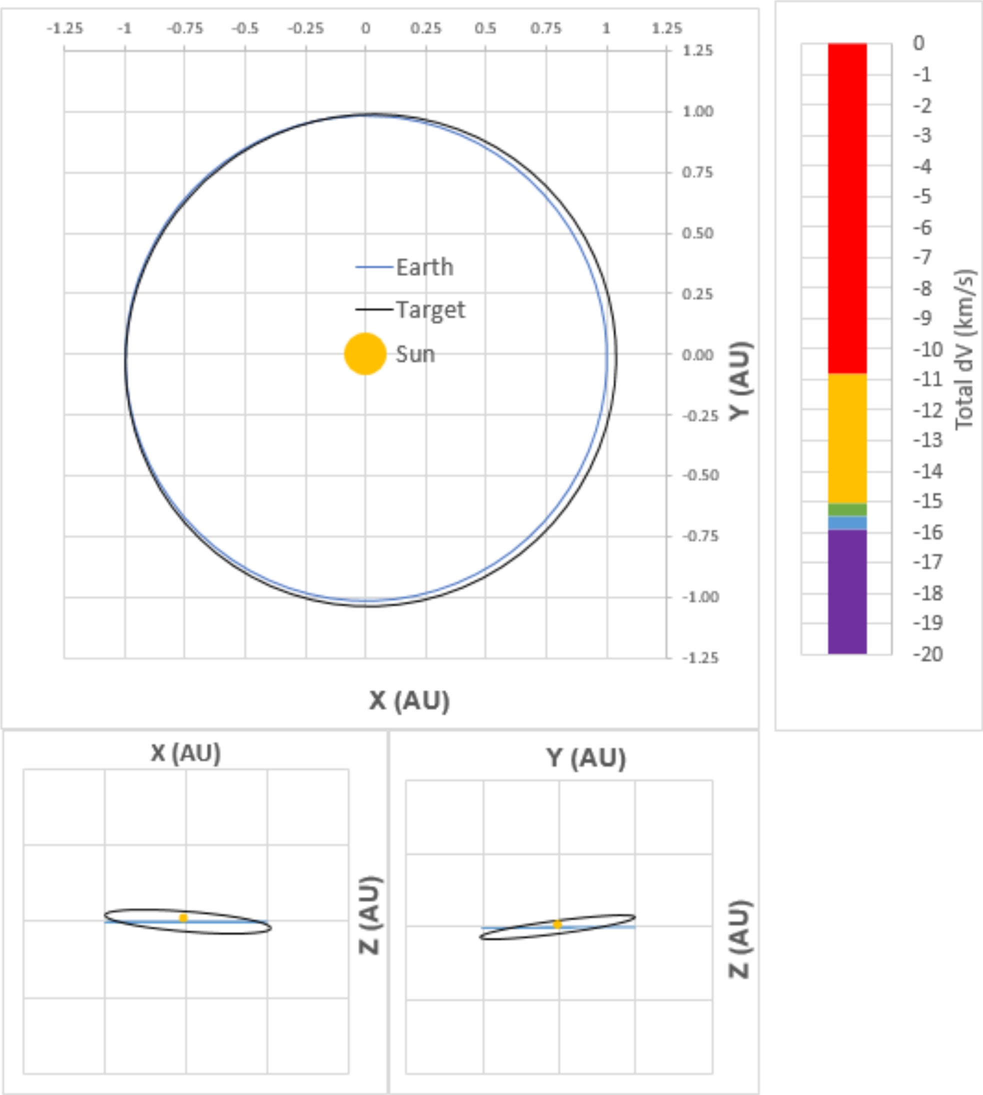


Figure 3-18: Part 3 or 3 of the Rock Finder front end for 2009UY19, showing the imported maneuver requirements for the mission. 2009UY19 had a preliminary trajectory computed as part of the NHATS study, so Rock Finder defaults to using these values. If the selected target is not in the NHATS study, values are computed in an external Lambert solver which duplicates the NHATS results for the requested target. Also reflected are the top-level assumption about which segments (launch vehicle, cislunar tug, Seed Craft etc.) are responsible for each maneuver. In this configuration, a cislunar tug is assumed to be available to intercept the empty RAMA craft and brake it into orbit after a lunar flyby. If these options are indicated as not available, the delta-v requirements are automatically re-apportioned, and the system reoptimized.

After 8 years, when the asteroid is ~50% hollowed out, the 750 kg electromagnetic bearing assembly[1] is detached from the Seed Craft and transported by the robots to the opposite interior of the asteroid. The base is welded to the interior wall, with its drive axis parallel to the spin axis of the asteroid. As construction continues, surplus iron and nickel from the smelter are combined with the remaining alloying elements from the Seed Craft to produce Inconel powder. Under robotic control using the Laser Engineered Net Shaping (LENS) technology from the manufacturing trade study in section 3.4.2, the powder is additively sintered radially outward from the electromagnetic bearing system, allocating the remaining metal composition of the asteroid into a single mass of metal, mounted on the electromagnetic bearing. The RAMA craft now has a crude mechanical spin stabilization and energy storage system.

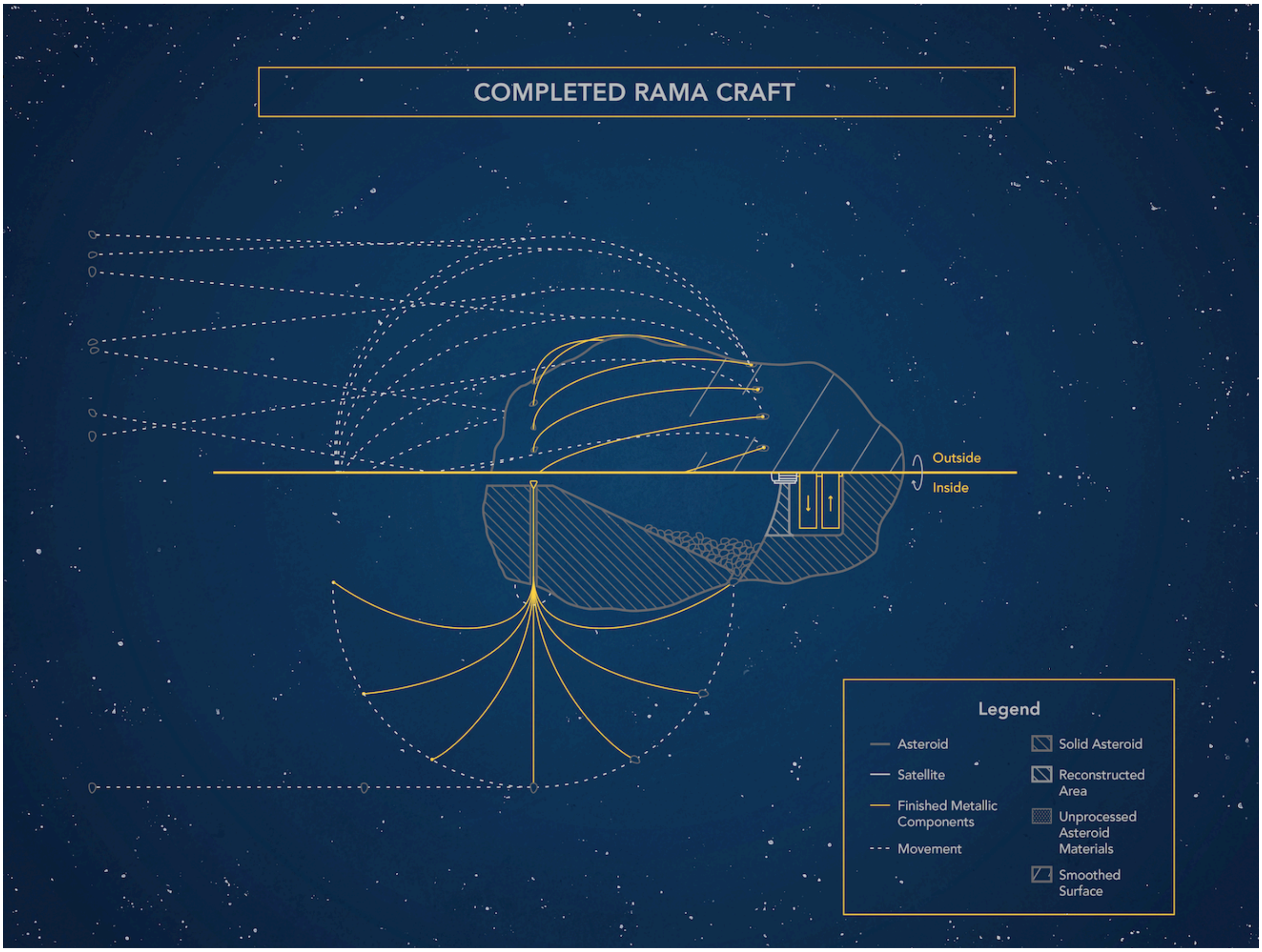


Figure 3-19: The completed RAMA spacecraft en route to cislunar space.

Construction of the RAMA spacecraft is now complete (Figure 3-19). During manufacturing, the Seed Craft has gradually used its own propulsion system to stabilize and orient the asteroid's spin axis in the correct direction. The system must now wait for the Earth return window to open. The Seed Craft stows

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[1] The Earth-built, Seed Craft delivered bearing assembly is just one way in which this mission case closes. The authors leave it to future study to investigate methods for in-situ construction of a capability to replace the need for this bearing assembly.

its solar panels to protect them from debris, powers down its manufacturing systems, and waits 13 years for the return window to open. During this time, it periodically reawakens to perform status checks and remote sensing operations on any other targets the asteroid may pass close to.

One month before the window opens, the Seed Craft wakes up, and redeploys its power systems. It now applies the power from the 4 MW photovoltaics (previously used to power manufacturing operations) directly to the motors in the flywheels. This power is applied for 25 days, at the conclusion of which, the two flywheel are spinning at ~4000 rpm (their approximate material limit) and have stored ~1 GJ of energy, the amount of energy required to return the asteroid to Earth. Slightly charging one flywheel over the other imparts a greater rotation to the reinforced asteroid shell, producing significant artificial gravity at the surface of the asteroid, further adhering the shots up against the interior of the asteroid and up against electromechanical exit ports bored by the robots.

Finally, the Seed Craft uses its own propulsion system to provide a series of forward “kicks” to the asteroid. These kicks impart no significant ΔV, but are properly timed to match the fundamental frequency of the 16 extended slings protruding from the asteroid. The slings begin to oscillate back and forth, and after 3 days of continuous kicks, the slings are rocking back and forth with a high enough amplitude to be bend all the way back to the asteroid’s surface. The slenderness ratio of the slings (250:1) is large enough to remain fully elastic when bent this far, allowing it to continue to oscillate like a pendulum with only thermal losses. The Seed Craft, its decades long task complete, disengages from the asteroid and departs for its next target.

The slings, once set in motion, oscillate at a period of 2.1 seconds, and at the peak of their swing, the tips are travelling at 312 m/s, achieving the theoretical maximum velocity of the material (Figure 3-20). At the extreme of each swing, the tip of the sling passes close to the exit ports near the asteroid’s equator, where extremely strong rare Earth magnets on the tip of each sling adhere to a single 10 kg shot. The strength of the permanent magnet on the tip and the remnant magnetism if the shot is calibrated such that the adhesion strength is exceeded exactly at the full extension of the swing, where the centrifugal force is maximized, hurling the shot astern of the asteroid at 312 m/s, and imparting a small but non-trivial 13 microns/sec ΔV onto the asteroid. At full “throttle”, with all slings operating, the asteroid accelerates at a constant 11 micro-gs.

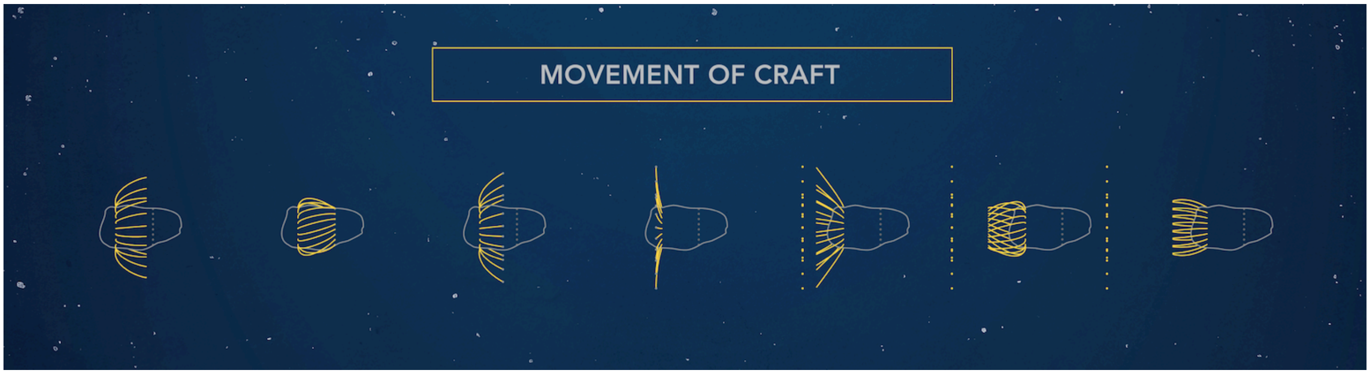
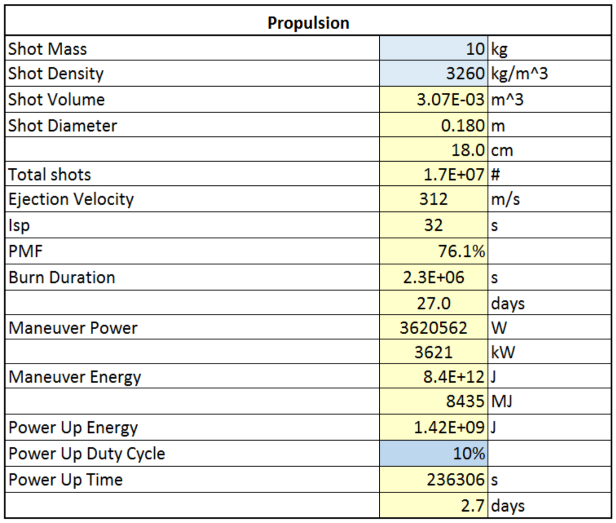


Figure 3-20: The movement of the RAMA spacecraft. The fluctuations of the sling arms back and forth would make the movement of the RAMA spacecraft look similar to a jellyfish swimming through the ocean currents.

This low impulse maneuver persists for 27 days. Each shot carries away a small fraction (0.55%) of the sling's energy with it. Over time, this loss will cause the slings to oscillating through a smaller arc and the asteroid to spin at a slower rate. To compensate for this loss of energy, the flywheels, which have remained spinning since they were charged by the Seed Craft, are slightly braked each time the slings reload, imparting a slight transfer of angular momentum to the asteroid itself, and thus to the swing arms. A summary of the sling performance as a propulsion system is shown in Table 3-19.

Table 3-19: Summary of the slings performance as a propulsion system from Rock Finder



Propulsion		
Shot Mass	10	kg
Shot Density	3260	kg/m^3
Shot Volume	3.07E-03	m^3
Shot Diameter	0.180	m
	18.0	cm
Total shots	1.7E+07	#
Ejection Velocity	312	m/s
Isp	32	s
PMF	76.1%	
Burn Duration	2.3E+06	s
	27.0	days
Maneuver Power	3620562	W
	3621	kW
Maneuver Energy	8.4E+12	J
	8435	MJ
Power Up Energy	1.42E+09	J
Power Up Duty Cycle	10%	
Power Up Time	236306	s
	2.7	days

This places the asteroid on an intercept path to Earth-Moon L5, where it is intercepted 249 days later after a lunar flyby by a cislunar tug. The asteroid at this point is considerably lighter (34,000 mT vs 230,000 mT) and the returned material is considerably "purer", as 90% of the asteroids worthless mass (its stone) has been ejected as propellant. The remaining mass is in the form of a pure metal flywheel and a hollow reinforced shell approximating the original shape of the asteroid, with an average wall thickness of ~4 m. The 30-year RAMA mission is complete, having delivered the mass equivalent of ~85 International Space Stations to the Earth-Moon L5 location.

3.6 C-TYPE ASTEROID MISSION ASSESSMENT

No detailed mission analysis was performed for a C-type asteroid, but the wider range of materials they present does permit for greater latitude in providing the RAMA crafts capabilities (note the greater frequency of C-type applicable technologies that were considered in Section 3.3.3). For example, up to 25% of the mass of a C-type is not inert rock or metal, but water-ice. Electrolyzing this water into hydrogen and oxygen, and them combusting them in a metal printed combustion chamber could produce much higher Isp than a mechanical system (340-380 s) allowing the asteroid to achieve ~100 m/s of ΔV by consuming only 25% of its mass. C-type asteroids are also known to be coated in a dark organic regolith composed of trace elements useful in the production of polymers and plastics. This would permit the production of plastics for structural support (making up for the lack of metals) or as a low performance solid rocket motor propellant. The dark and highly absorbing material also permits selective albedo control of the asteroid, providing a slow acting but "free" means to stabilize the asteroid with light pressure from the sun. Complete analysis of every one of these capabilities will be worked into Rock Finder in future work.

3.7 M-TYPE ASTEROID MISSION ASSESSMENT

Pure metal asteroids present similar challenges to S-type asteroids, as they offer limited materials for construction. The fact that they do not contain as much “waste” material as an S-type would further limit the propulsive options, and ejecting a significant fraction of the mass of the asteroid would mean disposing of much of the valuable metal that makes the asteroid of interest in the first place. Further complicating the issue is that M-type asteroids are rare among the NEO population, and tend to occupy the space in the main belt, thus requiring much more capable propulsive systems to return to Earth.

But in spite of these limits, M-type asteroid do present some interesting prospects for RAMA that warrant future investigation. For example, the combination of their relatively high albedo (0.3-0.4) and distance from the sun means their surfaces are typically much colder than those of other asteroids, so much so that their surfaces may exist under the brittle-ductile transition temperature of iron/nickel. If the iron-nickel surface of the asteroid is struck by an impactor while at this temperature, it will shatter into smaller fragments. Over billions of years, this process may leave M-type asteroids coated with a fine metallic powder, similar in size and structure to Lunar regolith. Such a fine metallic powder would be a perfect feedstock for a Direct Metal Laser Sintering (DMLS) or Laser Engineered Net Shaping (LENS) additive manufacturing process. Complex structures could be built directly onto the exterior of the asteroid with minimal materials processing or preparation.

For propulsion, the abundance of metals would permit the possibility of massive electromagnetic railguns, or iron powder based propulsion systems such as the VAST, Vacuum-Arc Plasma Thruster [31]. The need for ferromagnetic propellant would necessitate the loss of some of the asteroid’s valuable iron reserves, but the theoretically enormous ejection velocities and high performance enabled by this propulsion system would mean very little propellant needed to be consumed for a substantial ΔV.

3.8 ASTEROID HOPPING MISSION ASSESSMENT

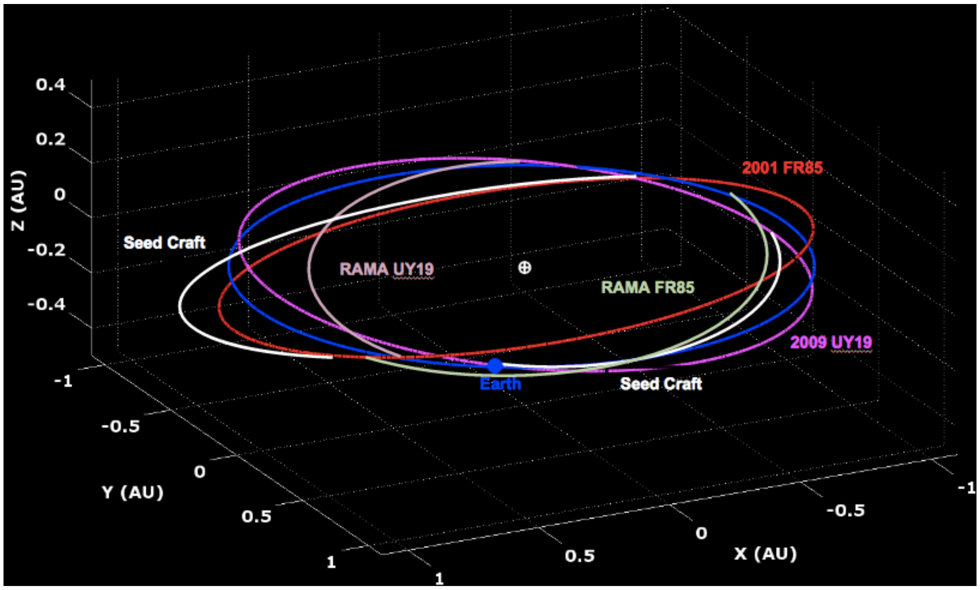


Figure 3-21: An opportunistic window for a Seed Craft to visit two asteroids in sequence: 2009UY19 and 2001 FR85. Each converted asteroid returns to Earth after conversion, and the Seed Craft continues to the next target without refurbishment.

The wide range of capabilities afforded by the Seed Craft's modular design does not limit it to one asteroid. In cases where an opportunistic launch window is identified (where it becomes possible to visit multiple asteroid in sequence without returning to Earth) then the Seed Craft can achieve even higher return on investment. An example of such an opportunistic window is shown in Figure 3-21.

Identifying these opportunistic windows requires computational resources that are beyond the capabilities of Rock Finder at the moment, but there is value in researching the option as a means to increase the RAMA systems ROI.

3.9 VALUE PROPOSITION FOR RAMA-BASED ASTEROID EXPLORATION

3.9.1 COMPARISON TO OTHER MISSIONS

Over time many missions have been proposed for retrieval of NEAs to the cislunar space. Most recently, the Keck Institute for Space Studies sponsored a study in 2012 using the NASA Asteroid Redirect Mission (ARM) architecture for returning a 500 metric-tonne asteroid to the Earth-Moon system [25]. The 2012 Keck study provided a detailed mission plan using technologies available over the next decade to formulate a mission to retrieve a 7-meter C-type asteroid and return it to the cislunar space for future prospecting use. Table 3-20 summarizes the comparable differences of the Keck ARM study to the RAMA architecture outlined in this report. The spacecraft (S/C) metrics refer to the Seed Craft within the RAMA column of the table.

Table 3-20: Mission Comparison of Keck ARM Study to RAMA

	Keck ARM Study	**RAMA Architecture**
Returned asteroid mass (mT)	500	57,500
S/C Power (kW)	40	1,000
S/C Mass (mT)	15.5	~50.0
Inbound ΔV (km/s)	0.2	0.47
Propulsion	SEP Hall Thrusters	In-situ Built Slings
TRL	6	2
Ratio of Earth Launch Mass to Asteroid Return Mass	**32.3**	**1,150**

The TRL of the technology from the Keck study is at a significantly more advanced state than the RAMA technology. With an overall TRL of 6, the Keck study approach is surely feasible in the very near term, while the TRL of 2 for the RAMA method warrants further development to reach mission readiness. However, the asteroid retrieval mass return of the RAMA method may out weigh the up front development cost needed to raise the TRL. The ARM approach is limited to ~15-meter size asteroids and smaller for retrieval, while RAMA may convert any size asteroid, even beyond the 100-meter size. Further asteroid detection work is needed to find plenty of 100-meter plus asteroid targets with high enough spin rates to ensure that they are solid masses and not rubble piles. However, current research shows that these 100-meter plus solid mass NEAs exist [26, 27]. The true benefit of the RAMA mission when compared to the current SOA missions, such as the Keck ARM study, is seen when factoring in the ratio of the asteroid retrieval mass to the Earth launch mass. The comparison shown here considers a Seed Craft approaching the mass of the Space Shuttle (~50mT) along with a very modest 75% propellant mass fraction (25% asteroid original mass returned to cislunar space). With these assumptions, **the returned asteroid mass is over 100x more for the RAMA mission than for the ARM mission**. Furthermore, the ARM mission would commence after returning the first asteroid while the RAMA Seed Craft would continue on converting more asteroids after sending the first one on its trajectory to cislunar space, essentially creating a steady resource retrieval chain with the requirement of just one Earth launch.

As described by the mission comparison with the Keck ARM study, there are two substantial benefits of the RAMA architecture over current state-of-the-art options for asteroid retrieval:

Mass Leveraging

The RAMA architecture allows for significant mass leveraging to occur by launching a relatively small Seed Craft from Earth compared to the size of the asteroid retrieved. RAMA allows for 1000+ MT asteroids to be returned by launching a ~50 MT Seed Craft, while the ARM architecture is capable of returning a ~10 MT asteroid by launching a 20 MT spacecraft. For humanity to truly harness the resource abundance of the asteroids it is critical to create technologies for retrieving resources of useful size for industrial processes.

One Launch vs. Many Launches

In addition to the mass leveraging capability of the RAMA architecture, the functionality of the Seed Craft allows for a perpetual cadence of asteroid retrieval with only one launch from Earth. This presents a significant advantage to all other proposed asteroid retrieval missions to date. Since the asteroid spacecraft is constructed entirely from in-situ materials there is little limit to how many asteroids one Seed Craft can retrieve.

3.9.2 RELEVANCE TO NASA TECHNICAL ROADMAP

Project RAMA represents a program that is fundamental to realizing many of NASA technology needs. The technological architecture of the RAMA concept is cross cutting with current NASA mission needs as well as push areas into new missions to grow NASAs current roadmap. Investment in RAMA technology development will simultaneously infuse capital investment into at least 7 NASA technology areas and into over 12 different NASA missions as shown in Table 3-21. Not only that, but the innovation of the RAMA concept will open up entirely new mission capabilities not currently on the roadmap. The retrieval of asteroids over 50,000 mT to cislunar space, made possible by RAMA, enables space habitats, large scale exploration space stations for deep space missions and new infrastructure to be created in space using space resources.

Table 3-21: NASA Roadmap Technology Areas, Missions, and Associated RAMA Capabilities

Tech. Area No. (T.A.)	NASA Mission(s) Enabled or Enhanced	RAMA Capability
1.4.1.1	DRM5-Asteroid Redirect	Long life capability reaction control built in-situ by the Seed Craft using asteroidal metals
2.3.7.1	DRM8a, DRM9, DRM9a, New Frontier: Push, Planetary Flagship: Push	Breakthrough Propulsion, In-situ created mechanical slings on asteroids
3.2.2.1; 3.2.2.2; 3.2.2.3	DRM6, DRM7, DRM8, DRM8a, DRM9, DRM9a	Large flywheels made in-situ
4.2.6.4; 4.2.6.5; 4.2.7.1; 4.2.8.3	Exploring Other Worlds, DRM7, DRM8, Planetary Flagship: Mars Sample Return	Mobility and manufacturing within the asteroid body
4.3.6.1; 4.3.6.2; 4.3.6.3;	DRM7, DRM8, DRM8a, DRM9, DRM9a, New Frontiers: Lunar South Pole Sample Return, Planetary Flagship: Mars Sample Return	Robotic Drilling technology on Seed Craft, Deep (100m) robotic drilling
4.3.6.4; 4.3.6.5; 4.3.6.6; 4.3.6.7	DRM7, DRM8, DRM8a, DRM9, DRM9a, New Frontiers: Lunar South Pole Sample Return, Planetary Flagship: Mars Sample Return	Sample acquisition, Sample handling, Regolith transfer from asteroid to Seed Craft for mfg., Seed craft robotic excavation
6.5.3.3	DRM7, DRM8, DRM9	Hollowed out asteroid used as radiation protected spacecraft shell for future human use
7.1.4.8; 7.1.4.9; 7.1.4.10	DRM7, DRM9, DRM9a, Exploring Other Worlds, Planetary Exploration	Solar powered sintering for soil stabilization
7.2.1.1	DRM7, DRM9, DRM9a, Exploring Other Worlds, Planetary Exploration	In-situ propellant harvesting
7.1.2.13; 7.1.2.15; 7.1.2.16; 7.1.2.17	DRM5-Asteroid Redirect, DRM7, DRM8, DRM9, DRM9a	Dust and soil separation via Seed Craft processes
7.3.1.5	DRM5, DRM6 Crewed to NEA, DRM8, Crewed to Mars Moons	Seed craft anchoring to asteroid technology
12.4.1.1; 12.4.1.4; 12.4.2.3	DRM5, DRM6, DRM7, DRM8, DRM8a, DRM9, DRM9a	Innovative metallic in-situ mfg. process, In-space assembly and fabrication using asteroid resources, Additive Manufacturing

3.9.3 BENEFITS OF THE RAMA PROGRAM THUS FAR

Though only nine-months in to the Project RAMA program, there are already strong benefits from the study work. The main benefit has been the creation of the Rock Finder tool. While Rock Finder was designed to work the RAMA mission scenarios it has been developed using the NASA asteroid database data. The tool itself is versatile and can be used for a variety of asteroid missions. During Phase I of this study outside organizations have began working relationships with Made In Space to utilize Rock Finder for other asteroid mission needs. Going forward, the RAMA team expects to build out Rock Finder to be a publicly accessible tool that the industry can continually update with new asteroid data is it becomes available.

3.10 RAMA TECHNICAL FEASIBILITY ASSESSMENT

The results reported herein represent the successful culmination of the proposed Phase I NIAC study. This study focused on a work plan designed to address the three main challenges to the RAMA concept; (1. How a mechanical spacecraft could be built in-situ, 2. Validating the mission concept, 3. Demonstrating a return on investment) and provide a viable path moving forward in terms of necessary technology development. The study has accomplished these objectives in the following manner:

- **Development of Rock Finder Mission Design Tool –** Rock Finder not only accomplishes the needed mission planning for a RAMA mission, but also may be used in future asteroid mission analysis throughout the greater aerospace community.
- **Feasibility of Creating Asteroid Subsystems In-situ** – A large trade study was performed on how to create spacecraft subsystems in-situ from asteroids. Each method was ranked across a variety of criteria, showing that mechanical subsystems can indeed be created and operate for certain mission types.
- **Assessment of ISRU Techniques –** The ISRU work performed adds new value and insight to the asteroid research landscape showing which asteroid types are candidates for which manufacturing methods in-situ.
- **Assessment of In-situ Manufacturing Methods –** A trade study on the variety of manufacturing methods that the Seed Craft could use for the RAMA process was completed that is ranked in terms of a series of ranking criteria.
- **S-type Asteroid Mission Assessment –** The asteroid 2009 UY19 was selected from a Rock Finder analysis for a RAMA mission. From the information developed in the previous steps of the study a full end to end RAMA style mission was developed for UY19.
- **Analysis of C-type, M-Type, and Asteroid Hopping Scenarios –** While not as in depth of a study as the S-type, the other asteroid types were studied and reported on for feasibility of a RAMA style mission.
- **Correlation to NASA Roadmap Needs –** An analysis of the NASA technology roadmap was undertaken, showing that there are over twelve different NASA missions and at least seven NASA technology areas directly impacted by the RAMA technology development. Funded work in RAMA means cross cutting technology development towards the larger NASA goals.

4 PATH FORWARD

4.1 BUILDING SUPPORT FOR RAMA

Project RAMA is such a novel concept that it can easily be taken for science fiction. This report should help dispel some of these beliefs and allow the aerospace community to consider the mission architecture as a viable future path for addressing asteroid resource utilization plans. For Project RAMA to reach a full level of viability a key part of the path forward lies in the need to build support for the concept. This requires a level of educational awareness and integration of RAMA concepts into the overall technology roadmaps within both NASA and the broader aerospace community.

4.2 TECHNOLOGY MATURATION PLAN

The technology drivers that will enable RAMA class missions to exist in the future should be tracked with an understanding of the rate of change of information enabled technologies as discussed in the introduction of this report. By doing so, estimates of time to technology maturation will be grounded in data on the exponential pace of technology developments in advanced robotics, artificial intelligence, computation, and manufacturing/resource processing. Based on these four technology areas, the following are trends that must be developed both in RAMA focused work and in the industries as a whole:

Advanced Robotics: The general trend of robotics today is towards further automation, increased dexterity, faster sensing, more accurate control, and lower cost hardware. These trends are all key to the success of the technology that will be needed for the Seed Craft to perform the RAMA conversion process. Furthermore, these technology trends must be adapted to in-space applications in the near term in order to raise TRL along with terrestrial growth. Programs like Made In Space's Archinaut program with NASA are key enablers for the advanced robotics technology to adapt to space use cases. Early use cases of Archinaut will be the foundation for future use cases of Seed Craft missions.

Artificial Intelligence: The originating concept of RAMA came from the recognition that a simple spacecraft could be made from asteroids by sophisticated Earth-built Seed Craft. For the RAMA spacecraft to successfully complete its mission, the Seed Craft must have a high degree of autonomous decision making and mission planning.

Computation: Technologists are often bad philosophers**.** We are overly optimistic with the general acceptance of new technologies and are sometimes off by decades of predicted outcomes. But if there is one area that we should be bullish with our predictions, it is in the area of computation. Gordon Moore showed that the there has been an exponential growth in computing for over 110 years with absolutely no signs of slowing down. Measured by calculations per second per $1000, there is a very predictable and very steady compounding capacity for computation. At this rate of growth, by the year 2040, when the first expected RAMA missions will be taking place, the average personal computer will have the computational capability of the human brain, or 10^{15} calculations per second. Therefore, advancements in computation capabilities should be tracked and well understood to anticipate Seed Craft performance capabilities when the initial RAMA missions begins. It is incredibly important to design RAMA missions knowing that the Seed Craft computation performance two decades from now will be far superior to what it could be today.

Manufacturing/Resource Processing: Despite several decades of robotic manufacturing and automation developments, the creation of goods is still very much tended by human labor. In many cases, humans remain in the manufacturing loop as feedback and process control. In other cases, the human is needed to maintain the manufacturing machines. Advanced robotic manufacturing technologies must continue this development path for the Seed Craft to be equipped with the necessary technologies for fulfilling the RAMA class missions. Pattern recognition, on the fly decision making, and automated control will make the Seed Craft capable of performing the RAMA conversion process which for some asteroids in a 10 year long continuous task done entirely without humans in the loop. Associated with these technology needs are the needs of advancing in-space mining and resource processing technologies. Without the ability to process the asteroid into manufacturing materials there will be no way to begin the manufacturing process.

4.3 OTHER MISSIONS ENABLED

While the Phase I study has focused primarily on the mission context of converting single NEOs for return to cislunar space, there are several other intriguing missions of interest. This section highlights four other missions that are enabled by the unique abilities of the RAMA architecture.

Altering Mass of “Super-Massive” NEOs

Calculations by Metzger et al. suggest that some NEOs would be too massive to alter their course using conventional chemical propulsion alone [32]. While this study has not focused on planetary protection applications, there is room for an interesting future study on using RAMA to reduce the mass of a potentially hazardous super massive NEOs, until it they fall within the bounds of current deflection technologies.

Asteroid Belt Scouting Mission

Detailed knowledge of main belt asteroids requires large space based telescopes in Earth orbit, or smaller scout spacecraft located in the belt. Therefore, there is a potential for a RAMA mission in which a Seed Craft is sent to the asteroid belt to manufacture these scout craft from asteroid materials. These scouts would remain in the belt, and respond to prompts from ground based telescopes. When a new asteroid is detected, the nearest scout could depart from its RAMA base and perform a multi-year transfer to the newly discoverer asteroid, providing data upon arrival on size, mass, spin rate, and composition characteristics. With enough asteroid scout craft located in the belt, equipped with basic sensors, the belt could be surveyed far more thoroughly than with exclusively terrestrial telescopes.

Human Exploration Missions

In 1964 Dandridge Cole worked out in great detail the mission architecture of hollowing out a large asteroid, spinning it along its axis to create artificial gravity on its inner surface, and then preparing it for use as a space habitat. Later work by Gerard O’Neill and others came to the same conclusion on methods for creating city-size space habitats. Meanwhile, NASA has a roadmap desire to enable long duration deep space human exploration missions. The RAMA mission described in this report looked at converting a 100m asteroid into a hollowed out spacecraft with a large flywheel for controlling energy and spin. Rather than using this RAMA mission for delivery of an asteroid to a space resource processing facility at L5, it could instead be sent to L5 to be outfitted with large solar arrays, communication infrastructure and terraformed internally with a pressurized atmosphere to become a space habitat for human deep space exploration. A new class of human exploration missions could ensue in which the astronauts spend many years within the RAMA space habitat, while it journeys throughout the solar system.

The Interstellar Extent of the RAMA Architecture – Self-Replicating AGI Space Exploration

The ultimate manifestation of Artificial Intelligence, known as Artificial General Intelligence (AGI) would enable a new class of RAMA style space missions. AGI systems are characterized by being good at learning and innovating on their own, much like humans do, and can become proficient at a wide array of tasks. By combining AGI with a Seed Craft capable of replicating itself with asteroid resources, it will be possible to create systems that can explore the far reaches of the galaxy with zero human intervention. RAMA missions of this class will be extremely sophisticated, capable of learning new things about the star systems they visit, selecting their own science goals, and making new decisions. One day we may send an AGI empowered Seed Craft to Alpha Centauri, where it will explore the star system, transmit its findings to Earth, replicate two new Seed Craft with AGI and resources available in the star system, before finally move on to the next two closest stars. This process continuing for perpetuity would enable the vast exploration of the galaxy at an exponentially increasing rate. Earth would relish in the steady stream of data being sent back from each Seed Craft makes while exploring new solar systems.

4.4 TECHNICAL CHALLENGES AND RISK ASSESSMENT

4.4.1 TECHNICAL CHALLENGES TO ADDRESS IN FUTURE WORK

This Phase I study aimed at studying the overall feasibility of the RAMA concept. Rather than doing a deep dive in any one challenge area, the work analyzed at a high level if it would even be possible to convert asteroids into large functional spacecraft. Technical challenges were always considered in the feasibility study; for instance, Rock Finder was developed to allow for mission planning to fully understand asteroid properties (spin, size, location, composition) to best design a Seed Craft and mission. With the Phase I work complete, and the feasibility analysis showing positive results for converting even the hardest of asteroids (very large S-types) into spacecraft capable of flying themselves to locations of interest, the larger technical challenges must now be addressed. The key challenges that future work should address center on (a) Mission Architectures, and (b) ISRU of Spacecraft Subsystems. Each is described below:

Mission Architectures: For the purpose of the feasibility of RAMA in Phase I, the mission chosen focused on converting a single NEA into a RAMA spacecraft capable of flying to the Earth-Moon L5 point. While the mission was shown to be feasible, it does not quite demonstrate a mission capability that is unique to the RAMA architecture. Future work must first and foremost focus on designing missions that could be enabled *only* by the RAMA methodology.

ISRU of Spacecraft Subsystems: Phase I presented an analysis of asteroid 2009 UY19 into a mechanical free-flying spacecraft equipped with metallic slings for propellant mass, and large flywheels for storing energy to power the slings. This mission analysis showed a very minimalistic approach to creating an asteroid spacecraft. It did without all other spacecraft subsystem, such as Attitude Control, GNC, C&DH. In order for the full vision of the RAMA concept to be developed it must be shown that key spacecraft subsystems can be built using asteroid materials in-situ. Initial investment should consider developing concepts for in-situ manufacturing of propulsion, energy storage, and attitude control subsystems, because of all the subsystems, these are the most mass intensive ones warranting in-situ fabrication. With these subsystems developed the S-type asteroid missions would reach a much higher TRL. The Phase I work has shown that it is possible to create mechanical gears and moving mechanisms using 3D printing and asteroid simulant. Phase I work also showed that basic navigation and avionics could be made to operate in full mechanical manners.

4.4.2 RISK ASSESSMENT

While there are a variety of risks for the RAMA mission architecture to come to fruition (programmatic, cost, schedule, and technical), the most important risks to invest attention to at this early stage are the technical risks. There are several yet undemonstrated technologies on the critical path, and the RAMA concept may be infeasible without each one of them. The following technical risks also align with NASA roadmap needs, so investment in burning down these risks will have a cross cutting benefit to other missions and roadmap needs.

>1 MW Space Rated Power Systems: The rate at which critical RAMA processes take place, such as the reduction of asteroid material and the production of RAMA craft components are not limited by mass or volume constraints on the Seed Craft, but by the power available to drive them. In order to convert the asteroid 2009UY19 in a realistic amount of time (<10 years) the Seed Craft required power systems with a rated output of 4MW, thirty times greater than the output of any electrical power system currently in space. If the RAMA architecture is to be extended to the main belt and Trojan asteroids, the use of solar power becomes less practical, and alternate sources such as nuclear RTGs will have to be considered.

Microgravity Metal Additive Manufacturing: Made In Space has successfully demonstrated the effectiveness of conventional extrusion based additive manufacturing methods in the microgravity environment using polymer and composite feedstocks. Microgravity metal manufacturing is also under development at Made In Space. In order to achieve widespread metal manufacturing in microgravity, large scale metallic parts must be able to be manufactured in-situ. The RAMA slings are estimated to be on the scale of 50m long. Today the leading metal AM methods rely on powder metal feedstocks, such as Direct Metal Laser Sintering (DMLS) and Laser Engineering Net Shaping (LENS). Powder methods pose completely different challenges in microgravity than extrusion based methods, including the hazard of free floating uncontained abrasive metal powder. Technologies must be developed to overcome these challenges to enable large scale metallic structures to be manufactured in space.

Optical Mining Technologies: As noted by Sercel et al., the Optical Mining technology needs to be demonstrated to higher power levels and longer durations (weeks or more). Additionally, the lens of the system need to be developed to out live the mission life of a multi-decade Seed Craft. We should expect to see investment in flight missions of this technology to raise TRL and establish it as a viable mining and manufacturing technique for asteroids.

Robotic Manufacturing of Large Assemblies: The Seed Craft design is based heavily on the anticipated developments of Seed Craft robotics and automated assembly of large structures. The SOA of robotic manufacturing and assembly is still relatively small; capable of building assemblies that fit within a room or high bay space. The flywheels of the RAMA spacecraft would be 10s of meters in diameter and would require a new level of automated manufacturing technology. Investment in this area has many cross cutting benefits to manufacturing uses on Earth (building construction, bridge construction, pipeline repair).

Asteroid Detection and Characterization: We are still in the very early days of having a full understanding of where the asteroids are, their orbits, spin rates, compositions, and size. The RAMA mission relies heavily on identifying asteroids of specific composition and knowing when their closest Earth approach will be. For large scale asteroids, beyond 100 meter in diameter, it will also be important to build a data set of such asteroids with fast enough spin rates to confirm that they are not rubble piles. The answers to these increased asteroid detection program will drive Seed Craft designs.

5 KEY FINDINGS AND CONCLUSIONS

Overall, the work performed provides a strong case for the feasibility of the RAMA concept. Furthermore, the study shows that there are both pros and cons to the RAMA architecture. For the asteroid 2009 UY19 for instance, it was shown that the full mission of converting it into a spacecraft and then having it fly itself to Earth-Moon L5 would be a mission lasting over 30 years. While a long mission, it would also return to the cislunar space an incredible material wealth far larger than the prospects of all SOA retrieval architectures. It was shown that the RAMA architecture is a novel and proficient way to move and control extremely large asteroids due to the fact that the propulsion system is manufactured in-situ and scales with the size of the asteroid.

Challenges still remain for the RAMA concept to be fully viable. There is a need for further mission development to reach full design specification of missions that are uniquely suited for RAMA style missions. The importance of doing this is to justify the investments into the RAMA technology path over orthogonal asteroid retrieval schemes. Along with this key challenge are the challenges of proving out the ability for in-situ manufacturing of mechanical spacecraft subsystems. This report showed that an asteroid spacecraft could be made from in-situ mechanical propulsion and energy storage. Advancing these ideas at a lab-scale is a critical next step. Attitude control and GNC are two other key subsystems worthy of future development as they may be tightly integral to the functions of the propulsion and energy storage subsystems. Addressing these challenges, and with proper focus, the RAMA concept will be fully capable in the next decade, which means that we could see initial asteroid conversion taking place only 15-20 years from now.

The idea for retrieving asteroids to cislunar space dates back to over a hundred years. Since the early days of the space industry engineers have designed missions to asteroids, calculated the theoretical mission needs, and have proposed utilization goals for once the asteroid is delivered to an orbital outpost. The near constant excitement and focus of these missions for such a long period of time signifies that it is a mission worthy of pursuing, but to close the gap from mission concept to mission execution will require a strong architecture that can absorb and amortize the large up front cost of development. Project RAMA is a novel architecture that not only enables the return of asteroid resources over 100x larger than all other SOA mission concepts, but also does so in a perpetual fashion enabling only one Earth launch vehicle to return many asteroids over time. Today Project RAMA needs investment to move from mission concept towards execution, but once these steps are taken it will enable access to the resource abundance of the solar system for many generations to come.

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