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Asteroid Mining

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This paper presents the results from the Phase 1 NASA Innovative and Advanced Concepts (NIAC) investigation for the Robotic Asteroid Prospector (RAP). The project investigated several aspects of developing an asteroid mining mission. It conceived a Space Infrastructure Framework that would create a demand for in space-produced resources. The resources identified as potentially feasible in the near-term were water and platinum group metals. The project's mission design stages spacecraft from an Earth Moon Lagrange (EML) point and returns them to an EML. The spacecraft's distinguishing design feature is its solar thermal propulsion system (STP) that can provide for three functions: propulsive thrust, process heat for mining and mineral processing, and electricity. The preferred propellant is water since this would allow the spacecraft to refuel at an asteroid for its return voyage to cislunar space thus reducing the mass that must be staged out of the EML point. This paper focuses on mining and processing technologies.

Nomenclature

ARM	=	asteroid retrieval mission
ARProbe	=	Asteroid Reconnaissance Probe
EML	=	Earth-Moon Lagrange libration point
GNC	=	guidance, navigation, and control
GCR	=	galactic cosmic rays
ISRU	=	in situ resource utilization
LH2	=	liquid hydrogen
LOX	=	liquid oxygen
PGM	=	platinum group metals
REE	=	rare earth elements
RAP	=	Robotic Asteroid Prospector
RTG	=	radio-thermal generator
TRL	=	NASA technology readiness level

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I. Introduction

THIS paper presents selected results from the nine-month, Phase 1 NASA Innovative and Advanced Concepts (NIAC) investigation for the Robotic Asteroid Prospector (RAP). The central objective is to determine the feasibility of mining asteroids. Ideally, this determination should be economic, technical, and scientific to lead to the conceptualization of robotic and later human asteroid mining missions. The paper distinguishes resources that can be used in space from those that could be brought back to earth and sold. The economic justification for the latter is difficult to establish at present. The value of a resource in space should derive from not its value on Earth but its usefulness in space. This value is analogous to the question: what is more valuable in the middle of Sahara desert -- 1 liter of water or 1 kg of gold. The paper presents the identified commodity resources available in space that are of potentially feasible economic interest, as well as a mining architecture and associated technologies for exploiting those resources.

A. Accessible Resources

The RAP team identified water as the commodity most likely to be of value for extraction and sale to customers in space for use as propellant. Platinum group metals (PGM) are the best candidates for potential sale on Earth, however the scope of the undertaking would require returning refined platinum or other PGMs to Earth in the 10s of metric tons. This amount of returned payload approaches 10% of the annual market. Given price elasticity, with an increased supply of PGMs, their price will drop. Any calculations for the economics of returning PGMs to Earth must take into account these supply effects on price.

Rare Earth Elements (REEs), although increasingly in demand on Earth, do not appear to be a viable candidate at this time because of the high cost and complexity of processing the ore. Additionally since the current cost of REEs extracted from the Earth is driven by the cost of the environmental remediation associated with that activity, there is the very real chance that reducing those remediation costs would be a more cost effective way to increase the supply of REEs than asteroid mining.

Future potential economic resources included scientific samples, regolith for radiation shielding, structural elements such as Al, Fe, Si, and Ti for in space 3D printing, processed water for life support, radiation shielding, and for propellant, and processed regolith for in space 3D printing of spacecraft structures. It should be noted that the strength of 3D structures in space does not have to be very high. This is because loads these structures will see will be relatively low. The required strength of spacecraft structures fabricated on Earth is driven by the launch loads and landing loads in cases when spacecraft lands on another planet.

With respect to where to find these resources, the RAP proposal baselined a set of telescopes in Venus orbit, looking outward from the Sun to identify and track the population of Near Earth Asteroids with far greater precision than currently available. Therefore, the RAP team was delighted when Planetary Resources LLC announced their startup in 2012, with a first phase of deploying the Arkyd space telescopes for this purpose. RAP looks forward to data from advanced versions of the Arkyd that could obtain albedo, rotation and spectrographic data for candidate asteroids.

B. Economics

The RAP team attempted to produce an economic demand model for the future “deep space economy,” based upon a notion of the infrastructure for human habitation of deep space and the per capita consumption of resources that infrastructure can produce and deliver in space. However, the team was unable to find sufficient economic data, a verifiable economic model, or the expertise to perform this demand model study. For example, it is extremely difficult to predict cost and schedule for developing metallurgical processes for PGMs extraction on Earth, let along in space. Metallurgical processes developed for extracting and beneficiating ores on Earth in majority of cases where result of years of “try and error” tests or luck.

Instead, as a starting point, the team decided to focus on water as the main resource (since extracting water is much easier than extracting PGMs or other metals) and created a parametric analysis based more simplistically on the price of water delivered to the International Space Station (ISS) from Earth and on the price of refined PGMs on Earth. Factored against these prices and assumed market elasticity (how much the price might change with an increase in supply) the team instead developed a parametric cost model to build, operate, and return the RAP spacecraft and its payload to the Earth-Moon system.

C. Mission Design

For any interplanetary mission, the energy cost of the mission is driven by the orbital position of the departure and destination objects. Having selected a destination, there is little flexibility in selecting a departure time.

Moreover, the length of the synodic period between the Earths and Asteroids orbits drives the time between mission opportunities, which can be extremely long, (i.e. decades or longer, for objects with similar orbit periods). Therefore, the RAP mission architecture encompasses a highly flexible approach to defining mission opportunities that uses multi-body gravity assists, multi-revolution interplanetary transfers and deep space maneuvers in order to maximize the number of mission opportunities while minimizing total mission Delta V.

An important part of this approach is the use of an EML point as a staging point for departing and returning mining spacecraft. This strategy provides significant reductions in Delta V when compared to missions departing from or returning to LEO. This reduction occurs because the EML points are located at the edge of the Earth's gravity well and a vehicle there is only loosely tied to the Earth. This significantly reduces the propellant required for those missions.

D. Spacecraft Design

The RAP team designed a prototype prospecting and mining spacecraft. It would implement a solar thermal propulsion (STP) system incorporating parabolic solar concentrators that can concentrate sunlight to 10,000x the incident insolation. The design of the RAP spacecraft enables use of this concentrated sunlight in three ways. First, it provides heat at up to 2500K to the solar thermal engine to expand the fuel out the nozzle to create thrust. Second, it provides process heat to the onboard mining, extraction, processing, and refining systems. Third, with a Stirling cycle engine, it can generate about one megawatt of electricity.. Water would be the preferred fuel for the STP system because it offers several advantages when compared to conventional propellants. Liquid water is very dense when compared to its cryogenic by-products liquid oxygen (LOX) and liquid hydrogen (LH2). Not only does it not require the complexity and cost of cryo-cooling, but also the mass and volume of the water tank structures can be much smaller than the tankage required for a comparable mass of LOX and LH2. Moreover, water can be stored in flexible tanks that simplify the task of propellant management in zero gravity. The RAP mission can launch these empty tanks into space in a collapsed state, significantly reducing the size of the fairing needed for the launch vehicle. The ultimate advantage of water as propellant for asteroid mining is that the RAP spacecraft can refuel itself while on a mission from certain asteroids, thereby reducing the propellant loading required at the outset of the mission.

E. Mining Technology

The mining approach varies a function of an asteroid size. For small asteroids of less than about 20 m in diameter, the spacecraft may capture it with a system of gripping arms and airbags. The mining operation would involve rendezvous with the target asteroid and orienting the spacecraft longitudinally at its pole along its axis of rotation. The RAP spacecraft would then spin up to match the rotation of the asteroid and then attach at the pole. For larger asteroids, the RAP will carry a set of small "spider" robots that can remove chunks of material from the asteroid and place them into the intake hopper to begin the extraction process. For both approaches, we recommend using Asteroid Reconnaissance Probes (ARProbes) to determine composition of the target asteroid and concentration of water and other compounds of interest.

II. Commodities Feasible for Production in Space

A. Commodity: Water

The first tier of commodities (Commodity 1) for in space use would consist of water as propellant for cislunar and interplanetary spacecraft. The demand for water for these applications, either to electrolyze into LOX and LH2 or to use directly as a propellant for solar thermal or nuclear thermal engines will become tremendous. This market assumes that the water collected from carbonaceous chondrites, from regolith ice, or from chemically bound sources, can serve as propellant with little or no post-extraction processing. In addition, water can be used to sustain human presence in space (i.e. drinking water) though this market would not be as large as propellant market because of the raw quantities required and over 90% of water can be recycled within a life support system. Water would also prove highly useful as radiation shield integrated into the crew habitat structure (Cohen, 1997), although this market is also subject to recycling of the water for shielding in other vehicles or for use in agriculture or life support.

B. Commodity : PGMs

Platinum group metals (PGMs) could potentially be valuable commodity on earth; however, it is impossible (at least for now) to determine that with any certainty. There are two major unknowns. First, it is difficult to evaluate the schedule and cost for developing metallurgical processes that will extract any of the PGMs in space. In fact, it is extremely difficult to evaluate cost and schedule for developing of any metallurgical processes on Earth (let alone for space). Second, it is difficult to foresee the prices change of any of the PGMs given high supply and if new markets of PGMs would be created as a result of price drop.

C. Commodity: Scientific Samples and Radiation Shielding

The second tier commodities of interest consist of regolith for radiation shielding in space and the same materials excavated from the surface of the Moon, Mars, asteroids, Phobos, or Deimos for scientific samples. Once a true cislunar, NEA, and interplanetary transportation system becomes available, the problem of delivering these commodities to the customers in space will become greatly simplified. Eventually, it will not matter where is the source of these and other commodities; the price to the customer will reflect that factor.

These scientific samples may include revolutionary, one of a kind new discoveries by deep space exploration vehicles. However, what is more likely, they will consist of samples extracted, hermetically packaged and preserved at suitable temperature, and returned for use in university and industry laboratories. The analogy to his type of market might be Doc Ricketts in John Steinbeck's Cannery Row (1945), who ran a business collecting specimens of marine life and selling them to university, pharmaceutical, and other industrial labs. Of course, RAP will not expect to find any life forms, but the idea is similar, to collect, process, and sell samples to researchers who are far from the source.

D. Commodity: Regolith for Radiation Shielding

Radiation shielding has emerged time and time again as the leading barrier to humans living long-term or permanently in deep space. During Mars Science Laboratory 253-day cruise to Mars, the Curiosity rover Radiation Assessment Detector (RAD) absorbed about half a Sievert.

An alternative solution will be to attach regolith tiles or bricks to the exterior of a space habitat module. Attaching these ISRU-produced shielding units can provide protection not only against the constant stress of GCRs, but also micrometeoroids, and even enhance thermal stability, reducing the need for cooling and heat rejection.

E. Commodity: Water for Radiation Shielding

Water presents the unique advantage for radiation shielding that it is amorphous: as a liquid it has no predetermined shape, as would be the case for regolith shielding. As a compound with a high content of loosely bonded hydrogen atoms, water offers advantages both for higher linear energy transfer (absorption) and a lower incidence of secondary particles compared to regolith. Although water shielding can be installed in the environmentally controlled interior of a spacecraft, that solution comes with the downside that filling water bladders will eat up much of the habitable volume within the spacecraft.

F. Commodity 5: Structural Materials

A critical milestone in establishing any type of settlement, colony, or civilization arises from the ability to build its own shelter and patterns of settlement. For many decades, including throughout the period shown on the Space Infrastructure Framework, only manufacturers on Earth will be able to produce pressure vessels for habitats in which the crew can live and work safely, productively, and happily. However, there will be many secondary facilities, structures, and civil works that the in space population will need. These facilities may range from a landing zone or pad made from sintered regolith to aluminum fuel tanks, cranes or derricks to support mining, manufacturing, fabrication, and assembly operations. These abundant structural materials include aluminum, iron, nickel, silicon, and titanium, among many elements found on the celestial bodies of interest. As the space-based demand emerges for new infrastructure on the surface of the Moon, Mars, or other bodies, the opportunity to source these facilities mostly or entirely in space will arise, in competition with sourcing from Earth.

It should be noted that many structures could be 3D printed using regolith fines as feedstock. These structures do not necessarily have to be as strong as on earth, since they will be used in zero gravity of space. In addition, the main drivers for spacecraft structures build on earth are loads the structure will experience during the launch on top of a rocket. Such loads will not be experienced in space, because the structure is already there. Another construction application of regolith would be to sinter it under intense heat into a quasi-ceramic material. The sintered regolith products could include ceramic masonry units (Allen, Graf, McKay, 1998), strengthened substrate on which to build structures (Ruess, Schaenzlin, Benaroya, 2006), "paving" of selected to reduce dust interaction with robots, landers, and crew, and possibly thermal insulation materials if it could include entrained gases.

G. Commodity 6: Water for Life Support and Agriculture

Commodity 1 exploited water for propellant with minimal post-extraction processing. For the life support application, the water will need considerably more processing to make it fit for human consumption or for use in drinking, hygiene, laundry, and agriculture. This refinement of the ability to provide "the universal solvent" to the deep space population will be a key to supporting and sustaining habitation permanently in deep space. Ideally, space colonies will choose to locate close to a good source of water, in much the same way as early settlers on Earth set up camp close to a river, spring, or other good source.

H. Commodity 7: Regolith for Soil

Regolith appears in Commodity 2 and 3 as a product for radiation shielding or scientific samples and feedstock for 3D printing of structures. However, there is another, potentially larger demand for regolith in agriculture. Under nearly all scenarios for deep space exploration, the crews will bring all the food they need with them from Earth. Surely, they may grow some vegetables in an aeroponic "salad machine" or other such relatively compact devise, but none of the prospective missions come close to thinking about self-sufficiency in food. Never the less, to establish a permanent colony outside the Earth-Moon system, producing all or nearly all the food will become a necessity for self-reliance and ultimately for survival. These colonies on the surface of a body with some gravity, however slight, will not need to be limited to the aeroponics that are de rigeur in microgravity. Instead, they can take advantage of the gravity – even partial G -- to feed water and nutrients to the plants' root systems. Instead of spraying water on the naked roots, these plants should be able to take root in a solid material. Certainly regolith with no organic material – let alone humus – will hardly suffice for soil, it may be possible to process the regolith to reduce or remove the reactivity of its oxides and other constituents such as perchlorates. Delivering regolith-derived soil for agriculture at permanent colonies or bases could furnish a valuable market.

III. Mining and Processing Technology

The RAP mining strategy takes the form of Figure 1 the Hierarchy of Resources and Markets. It lays out the tactical approach to each type of likely candidate resource and the corresponding markets on Earth and in space. The Hierarchy of Resources and Markets shows that in general, the resources obtainable from Asteroids can be divided into 4 broad categories: free water, bound water, metals, and regolith.

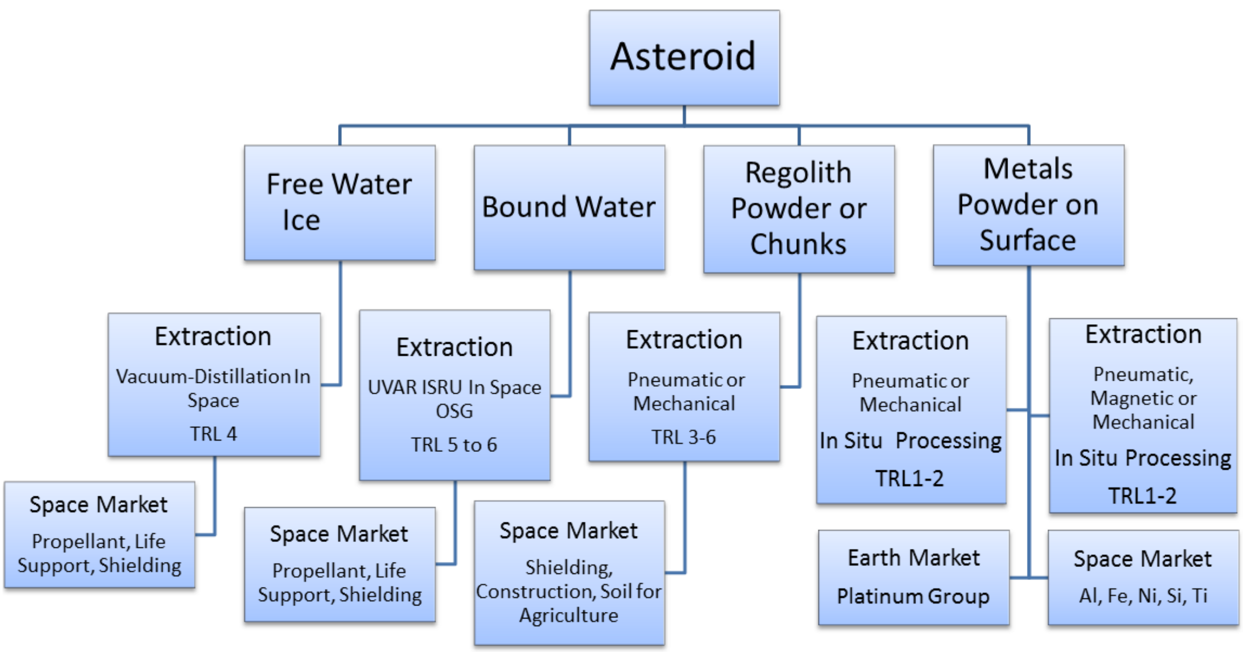

Figure 1. The Hierarchy of Space Resource Extraction and Markets.

It is a standard practice for terrestrial mines to organize mining operations around the main mineral product, while collecting bonus revenues from 'byproducts' of lesser concentration. In a similar vein, we will not travel all the way to an asteroid to mine just one resource. But neither will we be able to develop a "universal mining toolkit" that can extract and process any and all ores that we find on an asteroid or anywhere else. We will need to match particular technologies to specific deposits in selected locations. How do we align target body, the type of deposit, the mining technology, and what are the market and the price? On the other hand, the technology to grab and return different types of asteroids will be similar.

We also need to change the way we think about valuable commodities, and recognize the influence of location on value. Value on Earth does not equate to the same relative value in space. A simple analogy is this: What's worth more to a person stranded in the middle of a desert: a gallon of water or an ounce of gold?

A. Mining Functions

Mining of all types must follow these general steps: prospecting, excavating/mining, processing (e.g. comminution, concentration), extraction, and storage. Table 1 explicates these steps. Comminution is an energy intensive step and hence it should be avoided by mining pulverized regolith instead of small rocks or boulders.

Free water and bound water will be highly useful in the space environment for life support, radiation protection, and propellant -- either as electrolyzed LOX/LH2 or as liquid water for Solar Thermal Propulsion. The controlled extraction and processing technology associated with frozen water ice falls within the range of the relatively high Technology Readiness Level of TRL 4 component or subsystem laboratory test for vacuum distillation (which the RAP team accomplished during the 2012 NIAC Phase 1).

Table 1. Mining – Top Level Functions

Step	Description	Application to Asteroids
Prospecting	Finding and defining the extent, location, and value of the ore body.	Mineral concentration may be assumed to be relatively uniform on asteroids, unless some minerals are preferentially present in the fine or coarse fraction of regolith.
Excavation	Mining minerals from the ore body • Pneumatic methods • Magnetic methods (iron-nickel dust, nano-phase iron) • Auger, scoop, etc.	Options include excavating and extracting in situ, excavation ore for delivery to an extraction plant, or capturing the entire asteroid for delivery to an extraction plant.
Processing	Comminution is a particle size reduction of materials. It is extremely energy inefficient process and hence should be limited or eliminated altogether. Concentration is process of increasing the concentration of the wanted minerals. This includes magnetic and electrostatic separation.	Magnetic materials could be extracted using magnetic concentration process. Only fines should be captured using for example a magnetic rake. Electrostatic separation will be able to capture fines only and leave out larger rocks.
Extraction	Minerals: Extraction of valuable metals from their ores through chemical or mechanical means. Alloyed Metals: If metals are present in alloy form (e.g. Nickel-Iron) they must be de-alloyed.	If carbonaceous chondrite – water plus mineral extraction (titanium from Ilmenite, nano-phase iron) If metallic - difficult to de-alloy, hence use iron-nickel dust for 3D printing (structures can be much weaker in space than at 1g and no launch loads)
Storage	The refined resources is captured and stored within protective enclosure	Volatiles could be pressurized. Water is most likely going to be stored within pressure cylinders (so that it could be easily heated up and melted/sublimed). Processed ore could be stored in sealed containers to prevent losses.

Metals may be used in space to make structural components for spacecraft and spacecraft subsystems, or brought back to Earth and sold. The most ready-to-hand approach would be to extract regolith dust or powder, feed it into a 3D printer, and then sintered into various components for spacecraft (e.g. fuel tanks), structures (e.g. trusses), and habitats. Eventually, the technology will evolve to where it is possible to manufacture pressure vessel primary structure that is equal to aluminum, steel, or titanium counterparts made on Earth. The technologies necessary to mine minerals or metals, to extract metals from minerals, to de-alloy metals (from M-type asteroids), or to mine regolith and sinter it, are all at very low TRL. We do not know the cost to develop such technologies at present. However, the RAP team believes that initially, we can pursue the "low-hanging fruit" to establish a sustainable market. That low-hanging fruit is water.

Extracting free water is relatively easy – water ice can be sublimed and captured on a cold finger. Water extraction from hydrous minerals requires more heat, and so presents more of a challenge to achieve, especially if there is the potential for subsidiary reactions between liquid, vapor, or gaseous water and the materials from which the process is attempting to separate it. An example is Anhydrite or anhydrous calcium sulfate ($CaSO_4$) and Gypsum ($CaSO_4 \cdot 2H_2O$). When exposed to water, anhydrite readily transforms to the more commonly occurring gypsum. This transformation is reversible at ~200°C under normal atmospheric conditions.

B. Asteroid Mining Approaches

Figure 2 shows our approach to asteroid mining. In general, we envisage that small, inexpensive, fully robotic Asteroid Reconnaissance Probes or ARProbes, whether large or small, will initially study an asteroid, from orbit. These probes would be deployed from the RAP mother spacecraft, fly to a nearby asteroid, acquire samples from various locations, and fly back to the mother spacecraft. The analytical lab onboard the RAP mother spacecraft would study each returned sample to determine the exact fraction of volatiles and minerals. This information would then help the RAP operations team to determine the optimum extraction process and establish the initial value of the extracted and processed material.

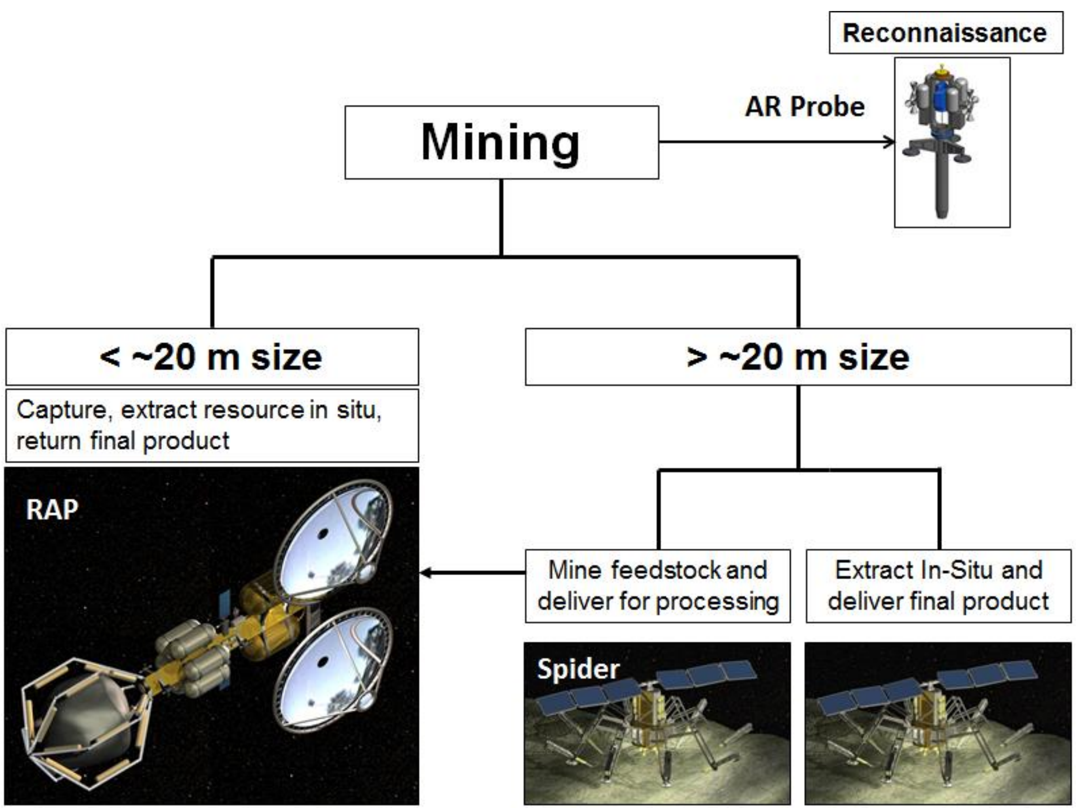

Figure 2. Asteroid Mining Approaches

After the initial reconnaissance step, the actual mining will proceed. The mining approach (and in turn the mining spacecraft) will depend primarily on the size of the asteroid to be processed. If an asteroid is less than approximately 20m in size, RAP could potentially "capture" the asteroid and process it in situ. There is an inherent limitation to capturing and mining such a small object. Assuming that the asteroid is a carbonaceous chondrite with the maximum expected water content of about 13%, the extractable water might not amount to a full return payload or even approach it. However, if the target asteroid is large enough to yield a full payload of water, it will be much too large to capture. In this scenario, the RAP mother spacecraft would deploy a team of smaller mining robot spacecraft, called Spiders. These Spiders could either deliver feedstock material back to the RAP mother spacecraft for processing. More advanced Spiders might process material in-situ and deliver only processed material to the RAP. Figure 3 shows a concept of the asteroid mining system: with Spiders and ARProbes.

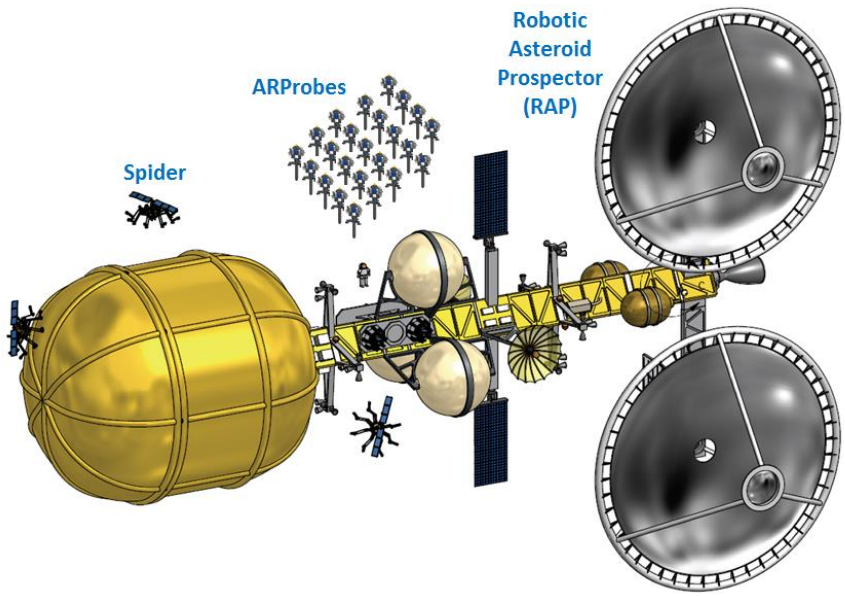

Figure 3. The RAP Spacecraft carries Spiders and ARProbes

1. ARProbes

Figure 4 shows the Asteroid Reconnaissance Probe or ARProbe. This probe will acquire a small sample of the asteroid's surface material for analysis and determination of the regolith mineral grade, fraction of water present, and whether it is a free water or bound water. ARProbes are fully robotic systems. They are small and inexpensive and hence the RAP spacecraft could carry 10s or 100s of them.

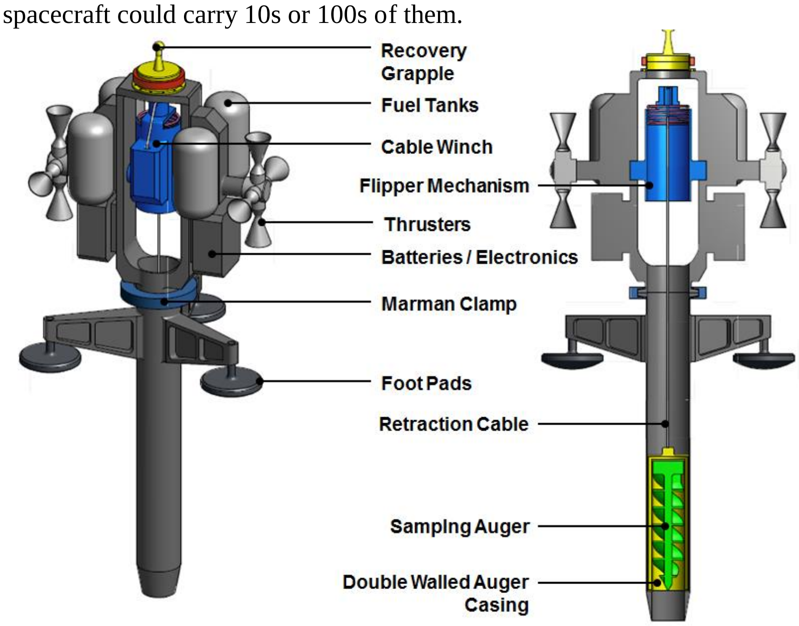

Figure 4. Asteroid Reconnaissance Probe (ARProbe)

The notional concept of operations for sample return from the surface of an asteroid appears in the following figures. The sequence begins with the parent spacecraft approaching the targeted asteroid. The parent spacecraft may spend several weeks to months orbiting the asteroid and analyzing it with remote sensing equipment, including cameras and stereo mapping. During this time, the RAP operations team will choose a potential landing site, based on the data available. Following landing site selection, the ARProbe will detach from the spacecraft as shown in

Figure 5, then uses its attitude control system to align itself for the descent towards the asteroid. The attitude control system will initialize a spin stabilization routine to both stabilize the descent and to aid in penetration of the probe into the asteroid surface. The onboard Guidance, Navigation and Control (GNC) system will control the impact velocity and coordinates on the asteroid.

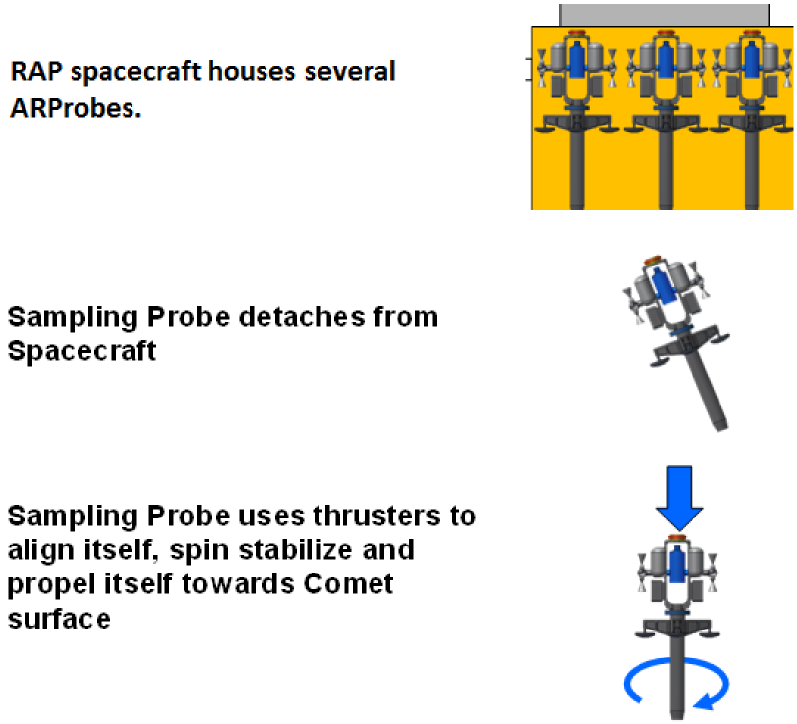

Figure 5. Concept of Operations – ARProbe Descent.

Flexibility will be highly desirable in final assignment of ARProbe excursions due to the relatively unknown physical properties of asteroid surfaces. The RAP operations team will determine the velocity of the descent based on results of laboratory testing, as well as visual and spectrographic imaging of the asteroid surface by the parent spacecraft to determine surface characteristics. If the asteroid consists of a loose conglomerate of fine particles, the RAP Ops team can command the velocity of the probe as relatively low. If the asteroid is dense, the RAP Ops team can command high velocities to insure penetration and sample acquisition. This architecture allows for a broad variety of asteroid surface characteristics.

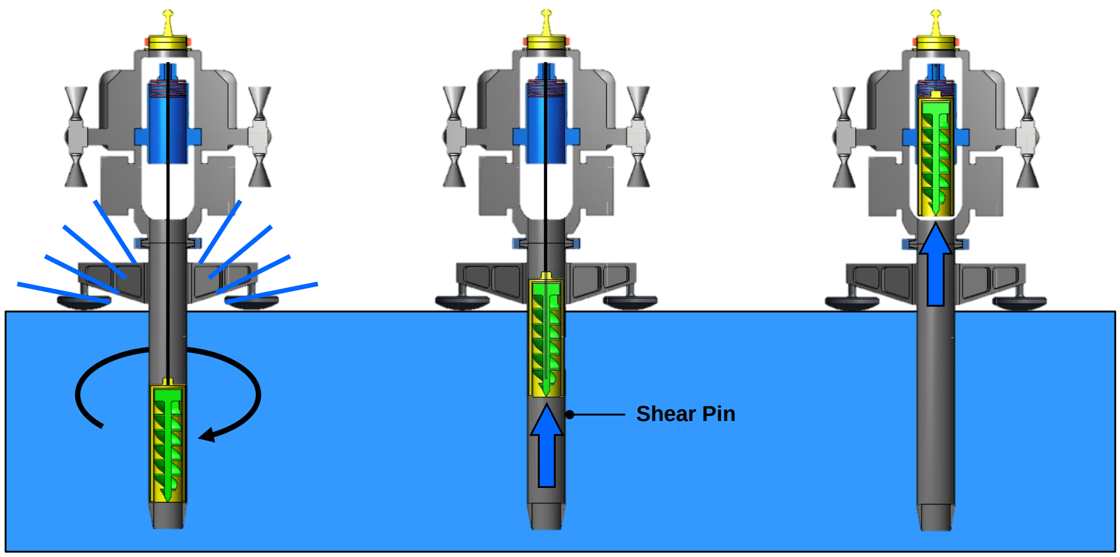

Figure 6. Concept of Operations – ARProbe Impact and Sample Acquisition

Following impact, the ARProbe sends a signal to the parent spacecraft alerting it to its successful contact and sending a system status update. The ARProbe then uses a cable winch mechanism to pull the auger and casing out of the asteroid and into the upper stage of the probe (Flipper Mechanism). When the auger and casing retract fully retracted into the upper stage, they compress a spring,, maintaining tension on the cable.

Once the casing retracts fully into the upper stage, preloading the spring,, the Flipper Mechanism rotates the entire canister and winch mechanism by 180 degrees. As soon as the Cap to the Casing is confirmed to be closed, the upper stage (Asteroid Ascent Vehicle) detaches from the lower probe body and travels to the parent spacecraft as shown in Figure 7.

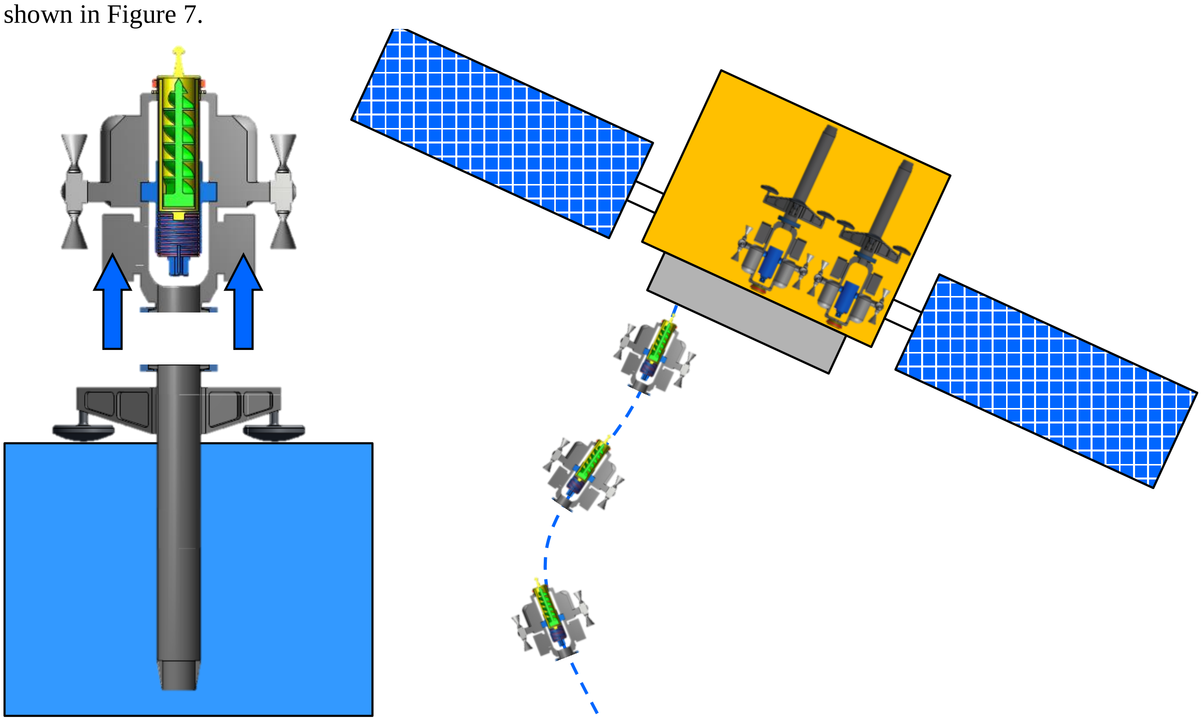

Figure 7. Concept of Operations – Upper Stage Release from ARProbes Impactor Stage and Rendezvous with a Parent Spacecraft.

2. Spiders

Spiders are robots that will follow to the asteroid surface after the ARProbes return their samples to the RAP mother spacecraft. Spiders have multiple flexible legs with deep fluted augers mounted at the end of the legs. The augers point inwards at an oblique angle. This geometry allows the spider's legs to anchor itself to the asteroid through a bracing action. In fact, the anchoring strength will only get stronger once the deep fluted augers are deployed and engage the subsurface to capture the surface regolith. The spiders can acquire loose regolith and either process it in situ or deliver it to the RAP spacecraft for processing.

The bracing system uses two or more multi-mode anchors positioned at an oblique angle to the surface as shown in Figure 8, resulting in a net force component along the asteroid surface. This resultant force braces the spacecraft to the surface. The advantage of this approach is that during the anchors' deployment only the force component in a vertical direction has to be overcome by, for example, firing rocket thrusters in the opposite direction.

C. Water Extraction

As Adam Smith (1776) stated famously "Nothing is more useful than water. . ." The same assertion holds true in space: water can serve multiple purposes, so many in fact that it can reduce the "parts count" for some other commodities or materials. These uses include propellant, life support, radiation shielding, and agriculture. Water can serve as fuel (LOX/LH2) for high thrust combustion or as liquid for Solar Thermal propulsion); it can be used for human consumption, and radiation protection. The in space propellant market – once it takes off – will bring a voracious demand for water. The market for water for life support will be more constrained because life support systems today achieve 90 to 95% recycling of water. The water for radiation shielding market will be similarly constrained because shielding water makes an excellent candidate for recycling and reuse. Once a crewed spacecraft returns to the Earth-Moon system on its last voyage (and presumably goes out of service), the crew can pump the water from the old vehicle to a new one, or to storage tanks for future reuse. The market for water for agriculture will include recycling, but as people begin growing their own food with a goal of self-sufficiency instead of resupply, the demand for water will grow tremendously. Still, only the market for fuel will involve a straight consumption demand, because once a spacecraft burns it or otherwise uses it up, a fresh supply becomes essential to continue piloting the spacecraft.

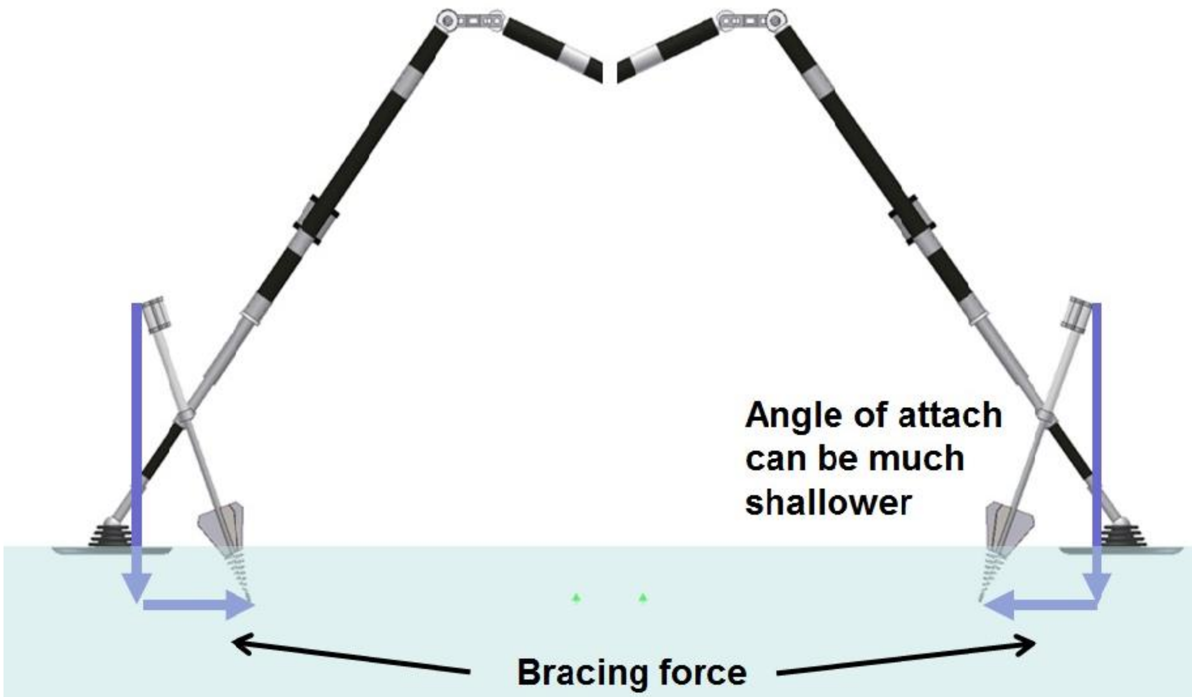

Figure 8. The Bracing Anchor engages the surface at an oblique angle.

There are two ways to extract water: Mine-Transport-Extract or Mine-Extract In Situ.

1. Captive Recovery (Mine-Transport-Extract)

First, an asteroid can be placed inside a bag and sealed. The RAP directs concentrated sunlight from from Solar Concentrators light directly into the bag. Coated on the inside with a reflective coating, the bag's interior helps to spread the light and thus the heat evenly. . Once the water in the captive asteroid starts to sublime, it will create its own pressure. The pressure difference between the bag and the condenser (cold finger) where the water is captured does not have to be high to channel the vapor into the condenser. Water extraction tests conducted in a vacuum chamber showed that a pressure difference of approximately 500 Pa was sufficient (Zacny et al., 2012). In addition, heat recovered from the condenser unit could be pumped back into the bag to enhance extraction efficiency.

2. In Situ Recovery (Mine-Extract In Situ)

The second method of water extraction, vacuum distillation, is to capture regolith that contains ice onto deep auger flutes. Figure 9 shows the several steps required to capture water. When the auger digs fully into the frozen regolith, it acquires the load of material for processing. Once fully loaded, the augur withdraws from the hole it drilled in the regolith and then retracts into a reactor. Heat from an RTG, electrical heater, or directed concentrated sunlight can then heat up the icy-soil to 0 °C. Further heating will allow ice to sublime and be captured on a cold finger. This particular technology has already been proven in vacuum and showed to work well (Zacny et al., 2012).

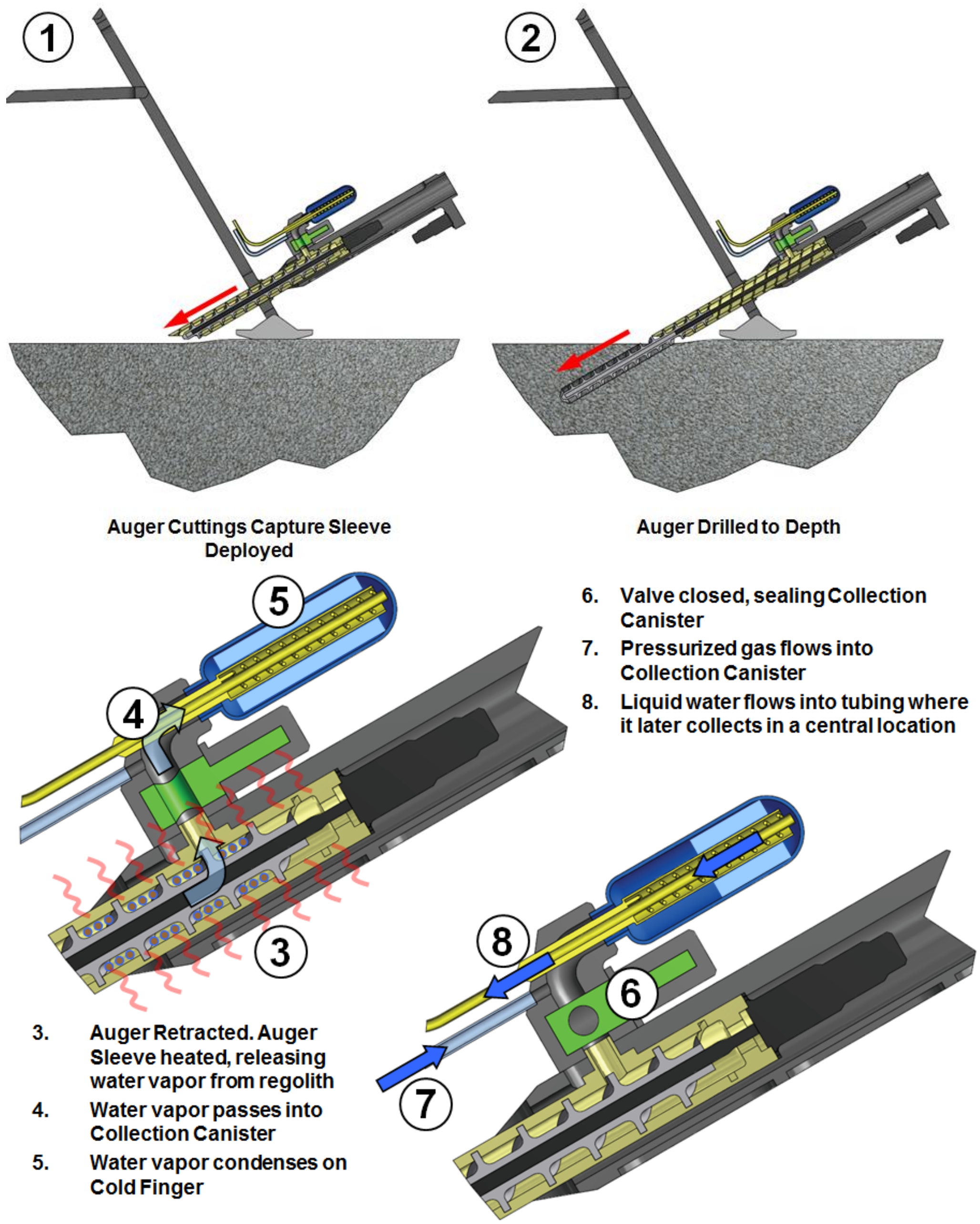

Figure 9. Water Extraction and Condensation Process

Table 2 shows the results of a feasibility study to determine the key parameters for water extraction from an Asteroid. The variables include the mass fraction of water in the asteroid, efficiency of a reactor (fraction of water captured inside a reactor), number of reactors, and size of an asteroid. To make the calculations easier to understand, the table uses 100 kg of water as an initial parameter – that is, the mission requires extracting 100 kg of water. In order to recover so much water, the RAP spacecraft (bagging) approach, would require an asteroid to be at least 3 meter in diameter. This metric assumes asteroid has 10wt% water and 50% of that is recoverable. Our estimates did not include the time required to accomplish that extraction – this is a fraction of energy that solar concentrators can deliver to the bag.

On the other hand, a Spider with 8 water distillation reactors, each 20 cm diameter and 1 m long, would require 3.3 days to capture 100 kg of water (assuming the same wt% water and efficiency cycle). This finding assumes 1 hour per each drill/capture regolith/extract water cycle. The energy required to sublime 100 kg of water with 90% energy efficiency is 83 kWh.

Table 2. Water Extraction Feasibility Calculations

		Water weight % in asteroid					
		1%	**2%**	**5%**	**10%**	**20%**	**22%**
Percentage of Water Recoved from an Asteroid							
Percentage of water captured inside reactor		50%	50%	50%	50%	50%	50%
Percentage of water recovered from an asteroid		0.50%	1%	2.50%	5%	10%	11%
RAP (Asteroid Bagging Option)							
Required mass of asteroid	tons	20	10	4	2	1	0.9
Bulk density of asteroid	g/cc	1	1	1	1	1	1.0
Required volume of asteroid	m3	20	10	4	2	1	0.9
Diameter of required spherical asteroid	**m**	**3**	**2**	**2**	**1**	**1**	**1**
Spiders (for larger asteroids)							
Auger (Reactor) diameter	m	0.20	0.20	0.20	0.20	0.20	0.20
Auger (Reactor) length	m	1	1	1	1	1	1
Auger (Reactor) volume	m3	0.03	0.03	0.03	0.03	0.03	0.03
Number of Augers/Reactors (i.e. Spider legs)		8	8	8	8	8	8
Number of spiders		1	1	1	1	1	1
Total volume captured	m3	0.25	0.25	0.25	0.25	0.25	0.25
Total mass captured	ton	0.25	0.25	0.25	0.25	0.25	0.25
Total water captured	ton	0.00	0.00	0.01	0.01	0.03	0.03
Number of auger mining cycles		80	40	16	8	4	4
Time per cycle	hr	1	1	1	1	1	1
Duration of water capture	hrs	80	40	16	8	4	4
Duration of required water capture cycles	**days**	**3.3**	**1.7**	**0.7**	**0.3**	**0.2**	**0.2**

The RAP spacecraft will be configurable to support either the asteroid capture strategy for captive sublimation or the Spider strategy for vacuum distillation. Figure 10 shows the required diameter of an asteroid for the RAP spacecraft concept and the duration of Spider cycles (for Spiders) required to recover 100 kg of water as a function of the water weigh % in the asteroid regolith. As the fraction of water in an asteroid increases, the required mass of an asteroid or duration of an 8-legged Spider cycle decreases. Note the maximum water fraction is 22% (Norton, 2002).

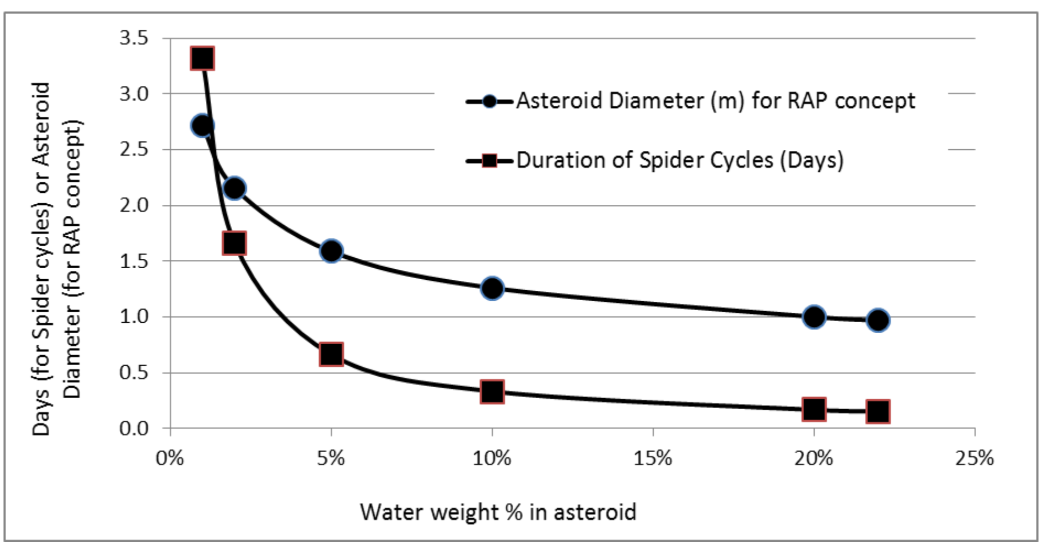

Figure 10. Diameter of an asteroid for the RAP spacecraft or duration of Spider cycles required to recover 100 kg of water as a function of water wt% in asteroid regolith. Water extraction efficiency assumed at 50% in both cases.

D. Metal Mining

Metal recovery in space will be extremely challenging. On Earth, gravity and water are key constituents of most terrestrial extraction and processing technologies. In addition, on Earth, the majority of metals occur in the form of various minerals and oxides. They need to be liberated and purified though a number of chemical processes. For example, Ilmenite is a crystalline iron titanium oxide ($FeTiO_3$). Standard mining processes extract Titanium from the Ilmenite by the following set of reactions:

$$FeTiO_3\ (s) + 3Cl_2\ (g) + 3C(s) \rightarrow 3CO\ (g) + FeCl_2\ (s) + TiCl_4\ (g) \tag{1}$$

$$TiCl_4\ (g) + 2\ Mg\ (s) \rightarrow 2MgCl_2\ (l) + Ti(s) \tag{2}$$

Terrestrial metal extraction and refining technologies took centuries to developed and implement to a level that makes them economically viable. For example, until Hall and Héroult developed a process for the production of aluminum, the metal was more expensive than silver. However, it took much experimentation to arrive at the best formula. The paragraph below bears witness to the complexity of the aluminum extraction process. The recipe does not include many details that go into making sure this process works, however, it does give a 'taste' of complexity.

In the Hall–Héroult process alumina, Al_2O_3, is dissolved in an industrial carbon-lined vat of molten cryolite, Na_3AlF_6 (sodium hexafluoroaluminate), called a "cell." Passing a direct electric current through it then electrolyzes the molten mixture of cryolite, alumina, and aluminum fluoride. The electrochemical reaction causes liquid aluminum metal to be deposited at the cathode as a precipitate, while the oxygen from the alumina combines with carbon from the anode to produce carbon dioxide, CO_2. The liquid aluminum is taken out with the help of a siphon operating with a vacuum, in order to avoid having to use extremely high temperature valves and pumps. The liquid aluminum then may move in batches or via a continuous hot flow line to where it is cast into aluminum ingots.

The electrolysis process produces exhaust that escapes into the fume hood to be evacuated from the working process environment. This exhaust is primarily CO_2 produced from the anode consumption and hydrogen fluoride (HF) from the cryolite and flux. HF is a highly corrosive and toxic gas, even etching glass surfaces.

Unfortunately, at this time there is no rule of thumb or a golden formula to determine how much investment and how many years is required to develop certain metallurgical process. This uncertainty is one of the major problems in extracting metals from Asteroids. Even if the target is an all-metallic M-type asteroid, asteroid miners will need to develop a process to de-alloy the asteroid (M type asteroids are made principally of an iron-nickel alloy). Metal alloy separation into individual metals is a complicated task, and is not feasible in space environment at this time. A simple, robust, lightweight, automated system for metal extraction and processing in space has yet to be conceived.. Potentially, one could skip the de-alloying step by processing the existing asteroid alloy into steel or other alloys, presumably by adding ingredients to it, heating, stirring, and cooling.

In addition to the complexity in developing any metallurgical process, the fact that the technology must work in microgravity and probably in a low pressure environment as well means that it require testing in LEO. Flying such complex and potentially hazardous experiments to the International Space Station would be extremely expensive; such research and testing would add millions of dollars and years to the R&D cost and schedule. In summary, it is extremely difficult to develop a metallurgical process for the terrestrial environment and it will be exponentially more difficult to do so for the space environment. These challenges contribute to the skepticism that mining REEs or PGMs would ever become profitable.

On the other hand, the space environment may offer some advantages, at least in the utilization of space-produced structural components. The spacecraft needs to be sufficiently robust to withstand launch loads at the top of a rocket. However, once in space, most components do not see major loading, save for a few (e.g. pressurized fuel tanks). Hence, space structures could in fact be made lighter weight and thus weaker since they would not need to withstand launch loads. In that case, 3D printing technology might well be suitable for space environment, particularly 3D printed elements have yet to come close to achieving the strength properties of metal forgings or laminated composites. In 3D printing, a feedstock material in the form of fine powder is heated up and melted and then printed layer-by-layer to form a structure. The feedstock to a space 3D printer could be fine asteroid regolith or a powdered metal. Such regolith could be mined with relative ease using magnetic or pneumatic mining techniques.

A concept of mining using magnetic rakes has been proposed before as well (Hartmann, 2000; Kuck, 1995). A magnetic systems, just as pneumatic systems, minimize moving parts and hence enhance robustness and reliability, which is vital when dealing with small and often abrasive dust. Since M-type asteroids contain magnetic Kamacite and Taenite, the magnetic mining could be very efficient. Of course other types of asteroids could also be targeted for metallic powders. Pneumatics can provide a method not only to collect but also concentrate the loose particulates from an asteroid, with gas recovery to enhance efficiency. Recent testing in the Honeybee Robotics laboratories revealed that 1g of gas at 50 kPa absolute could loft over 5000 grams of regolith in vacuum at high velocities. Unlike a magnetic system, a pneumatic system would work with any types of powder and it will provide required cut off particle sizes.

Finally the prospective demands of the in space commodities market can change the relative values and prices of commodities to different relationships than their prices on Earth. Presumably, the value of commodities in space will be established based on their usefulness in space rather than their price on earth. For example, aluminum is a much better structural material than gold, and in turn would be more valuable in space (even though it cost less than gold on earth).

IV. Conclusion

Technology for asteroid mining and processing is currently at very low TRL. Extracting asteroid surface materials is easier to do since it is more or less a mechanical/physical process and could be accomplished via various means such as magnetic, pneumatic, mechanical (scoop, rake, drill) etc. These approaches could be modeled and tested in zero-g flights and vacuum chambers.

Processing of regolith to extract free-water is at TRL 3-4 and has been demonstrated in vacuum. Since water vapor pressure and not gravity drives water extraction, vacuum-chamber tests in 1G can apply to the asteroid environment as well.

Metal extraction or de-alloying technologies are at TRL 1, basic principles observed. Metallurgy (the science of extracting and purifying valuable resources) does not offer a parametric equation to determine the time and cost for developing new extraction technology. Hence, it is extremely difficult to determine how much cost, how long a time, and even "if" a we can develop a for extracting and purifying metals on asteroid. Since potential technologies would have to be tested in zero-g, the cost and schedule for such a technology development would need to take these procedural bottlenecks into account.

Collecting regolith fines and printing 3D structures in zero-g would be feasible since 3D printing relies on a physical (melting/sintering) rather than a chemical process. MicroG prototypes could be developed and tested in microG parabolic flight planes and on the exterior experiment platforms of ISS (i.e. vacuum and zero-g).

Precious metal ores occur naturally at very low concentrations; that low concentration is a large part of what makes them rare and valuable. In terrestrial mining, the whole point of beneficiation, concentration, and the other processes on-site at the mine are to separate the ore from the slag, so that the expense of transport applies only to the useful ore. The same principle applies to Space Mining. There is no profit in returning the slag to the Earth-Moon system, only huge added costs. Therefore, we do not see an economic model for returning a whole asteroid to the Earth-Moon System, with the possible exception of capturing one for use as a testbed for mining technologies. This finding carries profound implications for the "Asteroid Retrieval Missions" (ARM).. This finding means that there is no realistic economic return in an ARM.

However asteroid retrieval may bring other, non-pecuniary returns. Such a mission may offer these benefits:

- Asteroid retrieval would be a fabulous engineering and operations challenge that will stretch and strengthen in space operational capability.
- The scientific value to examining a complete asteroid in depth, even a small one, could be immense. This investigation can inform the design of future asteroid exploration spacecraft and their missions.
- The asteroid can provide a testbed for astronaut training, providing great value in understanding the capabilities they will need on such a deep space mission.
- Most obviously, the retrieved asteroid can serve as a testbed for advanced prospecting, mining, extraction, and processing technologies in microgravity.

Despite all these inspiring and idealistic purposes for the retrieved asteroid, the RAP team could not find any scenario for a realistic commercial economic return from such a mission. The only scenario for making a profit appears to be all in situ mining, extraction, and processing to enable the delivery of finished products or commodities to the customers who will want them and pay for them.

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