The Hathor Excavator: A Mission Proposal for Asteroid Mining and the Space Launch System

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With NASA Space Launch System about to enter service, a whole new class of super-heavy payloads can soon be launched. Previously, missions beyond Earth and especially beyond lunar orbit were heavily restricted by mass requirements and were not capable of performing many desired goals. The Hathor Excavator is an exploration of one high-value mission that can be accomplished with the new launch vehicle. The Hathor Excavator mission sets out to demonstrate asteroid mining technology in large volume in order to pave the way for future government and commercial ventures. The Hathor Excavator integrates existing research with new innovative concepts to propose a plausible mission to accomplish these tasks.

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Nomenclature

$APXS$ Alpha Particle X-Ray Spectrometer

$CheMin$	Chemistry and Mineralogy instrument
FAA	Federal Aviation Administration
$FORM$	Fan Obtainment of Regolith Mechanism
GRS	Gamma Ray Spectrometer
$HEND$	High-Energy Neutron Detector
I_{SP}	Specific Impulse
$JWST$	James Webb Space Telescope
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
MSL	Mars Science Laboratory
RTG	Radioisotope Thermoelectric Generator
SLS	Space Launch System
$TAGSAM$	Touch-and-Go Sample Arm Mechanism
$VASIMR$	Variable Specific Impulse Magnetoplasma Rocket

I. Introduction

A. Mission Selection

The competition document describes the core objective as The objective of this project is to propose a space exploration mission beyond Earth and Lunar orbits utilizing large payload capability of the NASA Space Launch System. From this agenda, the requirements are few in number. The mission must:

1. Utilize the Space Launch System
2. Travel beyond the Earth and Moon
3. Explore space

The team proposed a total of eight potential mission that were developed and evaluated over the first few weeks of the project.

1. Mars Aldrin Cycler
2. Asteroid Mining Demonstrator
3. Europa Surface Lander
4. Interstellar Probe
5. James Webb Space Telescope (JWST) Servicing
6. Martian Moon Habitat
7. Uranus Orbiter
8. Venus Atmospheric Explorer

The mission proposals are concisely outlined in the following passages.

1. The Aldrin Cycler mission would involve placing a human rated habitat and propulsion system into a special trajectory that constantly ferries between Earth and Mars. Such a spacecraft would only need a small amount of propellant to keep on the trajectory. Buzz Aldrin advocates setting up these kind of craft to make future Mars missions more sustainable. However, the mission would require a very complex human-rated habitat to be launched aboard the SLS and the mission is dependent on the United States journey to Mars requiring aldrin cyclers.[1]
2. The asteroid mining mission would launch an unmanned robotic craft out to a near Earth asteroid, and gather a large portion of material. The material would be returned to low Earth orbit and processed to some degree. Such a mission could remove some major hurdles for future commercial ventures in asteroid mining such as Planetary Resources and Deep Space Industries. This mission would require complex mechanisms in order to interact with a variable surface on a generally unexplored asteroid.[2]
3. The Europa surface lander mission would send a robotic probe to Europa, the second moon of Jupiter, and attempt to land on its surface. It may be feasible to drill a borehole down through the icy crust, and attempt to directly observe the subsurface ocean. The mission would be a high-profile planetary science mission with a large amount of enthusiasm behind it. Subsurface oceans are one of the few environments in the solar system that are potentially habitable, and are therefore valuable scientific targets. Difficulties arise from attempting to design a planetary lander in addition to a borehole mechanism.[3]
4. The interstellar probe aims to accelerate a small robotic probe to speeds that could be practical for interstellar travel. The mission would mainly surround testing a very high power and efficiency propulsion system. Such a mission would push the capabilities of propulsion technologies, and also inspire public opinion in space travel. There is one major challenge for this mission, and that is developing a propulsion system capable of accelerating any object to over a hundred kilometers per second.[4]
5. The JWST Servicing mission would launch a manned crew out to Earth-Sun L2 for a 70 to 80 day mission repairing or upgrading the telescope. The mission provides the opportunity to lengthen the operating life of a telescope that would match Hubble in scientific discovery as well as provide a short term environment for testing deep space equipment for future manned missions. The mission would face challenges dealing with the highly sensitive orbit, the instruments on the JWST, and working with components not designed for periodic service.[5]
6. The martian moon base mission would assemble a human-rated habitat and deliver it to martian orbit, or preferably on a martian moon. The forward base would serve as a critical staging point for future Mars

missions, creating an easier to reach site for experimentation and a location to utilize telerobotics on the martian surface. The mission would be close to the limits of what two SLS vehicles could launch, navigating the low-gravity and uneven surface of martian moons with a robotic craft would be very complex, and the mission is partially dependent on the United States specific Mars mission architecture.[6]
7. The Uranus orbiter mission would be a planetary science mission to the ice-giant of Uranus. Utilizing the SLS allows for a direct transfer rather than a series of planetary slingshots, and allows the mission to have the capabilities of up to a flagship class mission. Uranus has only ever been observed via flyby, so the first orbiter would make a large amount of scientific discoveries about the outer solar system. This mission would be challenged by very long signal delays between the ground and the spacecraft, and the navigation of a less-understood moon system. The mission would also have to be significantly more beneficial than one which uses the planetary slingshot method to merit using the SLS.[7]
8. The last considered mission would send a high-mass planetary science mission to Venus upper atmosphere. Exploration of the atmosphere would be conducted by balloon craft. Similar missions have been proposed and executed in the past, but this mission would utilize multiple balloons at different geographical locations and stay aloft for significantly longer, on the scale of months or more. In-situ exploration of Venus would yield atmospheric characteristics of the planet that are simply not possible to measure from orbit. Difficulties in the mission arise from dealing with the incredibly hostile environment of Venus for an extended duration. Additionally, the mission may be better suited for a smaller launch vehicle due to the closeness of Venus and the inherent low mass in a lighter-than-air robotic explorer.[8]

The missions themselves were weighted on 3 main metrics: the feasibility of the mission (which includes number of launches, manned compatibility, difficulty of task proposed), the potential cost of the mission, and the total benefits of the mission (in terms of scientific, economic, and cultural benefits). A basic analytical hierarchy process weighing all three metrics as equal was conducted as shown in table 1. However, the team came to a decision after deeper investigation into the implementation of each mission proposal.

Table 1. Analytical Hierarchy Evaluation of the Eight Mission Proposals.

Mission	Feasibility	Potential Cost	Total Benefits	Score
Mars Cycle	4	2	2	8
Asteroid Miner	5	6	8	19
Europa Probe	6	3	4	13
Interstellar	1	4	6	11
JWST Service	3	8	7	18
Martian Moon	2	1	5	8
Uranus Orbiter	8	7	3	18
Venus Probe	7	5	1	13

In the end the asteroid mining demonstrator was chosen as our ideal mission due to its unique benefits that could not be found in other missions. The following is a list of reasons as to why the other missions were not considered.
1. The team decided that the two martian missions would not yield benefits of equal magnitude compared to the other choices as they are dependent on NASAs current and uncertain mission architecture. The future mission plans for Mars may or may not require an Aldrin Cycler or a forward base on one of the martian moons, so such a mission may not have agency backing in the the near future.
2. Along a similar line of reasoning, the servicing mission to the James Webb Space Telescope would also be suboptimal. Unlike Hubble, which this mission proposal was inspired by, the JWST is not designed with easily accessible circuits and instruments. As such a servicing mission to the telescope would be far more difficult than the Hubble repair missions. Depending on the problem with the telescope, some repairs may not even be possible with a manned mission.
3. The interstellar probe concept was eliminated due a high amount of technical difficulty and very little benefit. Unlike the other missions, the only benefit of this mission would be as a technology demonstrator. Such tests in propulsion can be more cost effectively conducted on the ground with far less risk involved.
4. The most attractive mission proposals came down to the three planetary science missions and the asteroid

mining mission. The planetary science missions were not as reliant upon the space launch system and could possibly be conducted by lighter launch vehicles. The Europa proposal has a lot of overlap with with the currently in development Europa Clipper mission, while still having a high factor of risk. The SLS allows the Uranus Orbiter to reach the outer gas giant in less than half the time of traditional trajectories that need to utilize planetary slingshots. But a mission using that method is far from infeasible as orbiters have been sent out as far as Saturn using gravitational slingshots. The Venus proposal does not need the entire capability of the space launch system in order to complete its goals, due to its close proximity to Earth and the lighter-than-air requirements of the payloads being delivered.

The asteroid mining demonstrator has the potential to spur economic benefits in addition to scientific ones. This mission would set forth the methods in which asteroid mining can be conducted. Existing organizations that have declared their purpose to utilize the resources in space, but have not been able to move forwards due to the uncertainty of the practice, will be able to utilize the experience from a government-funded demonstrator and use it to further their ventures. The mission would demonstrate the practices to autonomously collect asteroid material, and the processes of turning it into useful components such as water for future space industry.

B. Mission Requirements

The requirements proposed for the mission include:

1. The exploration mission objective/destination must be beyond Earth and Lunar orbits.
2. Proposed exploration mission architecture and timeline is constrained by the total mass and volume capability of no more than two SLS Block 1B launches occurring no earlier than 9 months apart.
3. The exploration mission can either be crewed or robotic. Depending on mission objective, basic considerations for life support systems, robotic systems, and scientific payload must be considered.
4. While not constraining for the purposes of this project, basic consideration should be given to scientific merit and economics of the proposed mission.
5. Reliability, affordability, and ease of operation for the mission should be considered.

Once decided upon, the Hathor Excavator went under review to refine the specific goals that it should accomplish. In order for the mission to pave the way for future asteroid mining missions, it must accomplish the following tasks.

1. Travel to an asteroid
2. Land and attach to the asteroid
3. Collect a significant amount of material from the asteroid
4. Demonstrate some capability of separating materials into components
5. Return processed materials to an accessible location

C. System Overview

The mission proposal is called the Hathor Excavator, named after the egyptian god of mining, the sky, and fertility. The egyptian mythology theme also ties into the name of the target for Hathor, the asteroid Bennu. NASA used the same naming theme for the precursor mission to the Hathor Excavator, OSIRIS-REx.

The Hathor Excavator is a 30 metric ton spacecraft costing an estimated 3.5 billion USD. It is powered by two large solar arrays used primarily for its VASIMR electric propulsion system. The spacecraft communicates primarily through X-band radio to NASAs Deep Space Network. The spacecraft utilizes a dumbbell shape with one half containing the propulsion equipment and the other containing the asteroid operations equipment. The spacecraft is capable of just over 7 km/s of ΔV from its argon tanks and is expected to collect up to one metric ton of asteroid regolith using a portion of the 1.1 tonnes of on-board nitrogen through its collection system.

The collection system consists of a 15 m arm that is able to rotate along two axes. Attached to the arm is a device called the Fan Obtainment of Regolith Mechanism (FORM) which collects asteroid dust by launching it free of asteroid Bennu via compressed gas and collects it with an impeller connected to a dust collection system. The FORM is able to translate along the arm allowing it to sweep over a large area of the asteroid's surface without the spacecraft having to move. A second arm and FORM is on the other side of the spacecraft for redundancy.

The Space Launch System becomes a crucial component in completing these mission points due to their high complexity. A system could not be minimized to the category of light payload and still accomplish everything that is designated above.

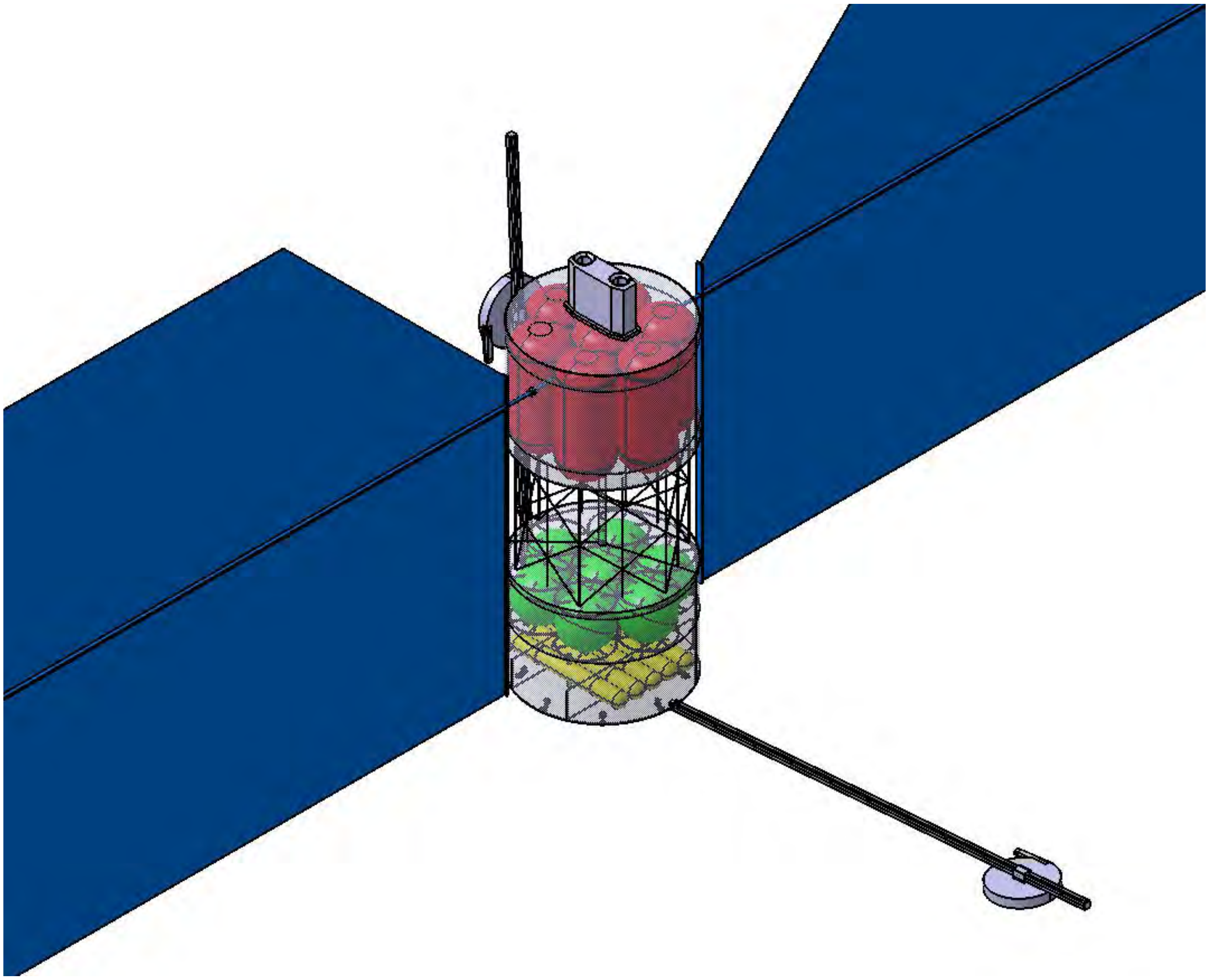

Figure 1. CAD Model of the Hathor Excavator.

A brief timeline of the mission follows. Further details can be found in the orbits section of this proposal.

June 2023 - launch
August 2023 - use the SLSs exploration upper stage to perform Bennu injection
October 2024 - orbital insertion at asteroid Bennu
December 2024 - landing on Bennu begin mining operations
February 2025 - finish mining operations launch from Bennu
February 2025 - Earth injection burn
May 2027 - Earth arrival in parking orbit

II. System Dynamics

A. Asteroid Selection

Once the mission objectives were determined, a suitable target-asteroid was the next priority. For asteroid selection, the primary source of information can be accredited from Asterank, a website that gathers and organizes data from the JPL Small Body Database.[9] Asteroids were initially chosen based on the criteria determined by the team and requirements given by the AIAA. After narrowing down the contending choices to an initial group, four asteroids fit the best: 1989 ML, Bennu, Itokawa, and Ryugu.

A couple factors which were considered in determining which asteroid to travel to, is that the asteroid must be feasible to mine and accessible to land on. As determining the composition of a sample from the asteroid is the primary focus of the Hathor Excavator mission, it is also essential that there is a high possibility the targeted asteroid contains hydrocarbons and or metals to enumerate the value of the mission. The superlative compound sought after with this mission is nonmetals, which can be turned into rocket fuel for other space missions. Furthermore, the suitable asteroids considered must be beyond lunar orbit as identified by the criteria of the mission proposal, yet preferably within Mars orbit. An asteroid with a smaller semi-major axis is a good indicator of distance, as it helps quantify its orbital path. More so, an asteroid which experiences a lower ΔV would be considered superior to those which have a higher ΔV, as a slower speed suggests an easier landing on the asteroid.

To understand why the metrics were chosen, it is a good idea to look at some of the more valuable asteroids listed on Asterank. For a mining mission, it would seem to make sense to pick asteroids that were incredibly high in value. The more valuable an asteroid is, the more income can be gained from harvesting it. The problem with many of these high value asteroids is that they get most of their value from metals and they are harder to travel to and land on. For example, David and Chicago, two asteroids considered high value, are more rich in metals like cobalt and nickel than they are in nonmetals.[9] While metals are important, one of the goals of this mission was to demonstrate the possibility of making rocket propellant in space. For that, the mission needs a focus on nonmetals, which can be found in more abundance on smaller, less valuable asteroids. These asteroids are also much harder to get to. Davida, for example, has an orbit outside of Mars orbit, has a ΔV over 10 km/s, and has a large inclination of 15°.[9] Going down the list, many, if not all, of these high value asteroids are the same way. These values make travel and landing harder. The four initial asteroids, while not considered the most valuable, are the most reasonable choices for the mission.

While all four asteroids contained some material that was of value for future missions, the S-type, Itokawa and the X-type, 1989 ML were eliminated from consideration. Both of these asteroids contained large amounts of iron and other metals, yet neither contained large amounts of nonmetal materials.[9] Hydrogen, oxygen, carbon, and nitrogen are all important elements for the creation of propellants needed for in-space travel; therefore, these elements are the primary targets of the asteroid mining mission. Theoretically, if these elements are mined on asteroids, propellants and oxidisers can be produced in space, allowing for future missions to refuel while away from Earth; an example of this would be for missions traveling deeper into space.

Ryugu and Bennu were found to be the most similar asteroids in multiple aspects. Both are rich in nitrogen and hydrogen, both contain metals, both are within Mars orbit, both have upcoming near-Earth approaches, and both have similar tilts to their orbits as shown in figure 2. Unlike Bennu, Ryugu is easier to travel to with a lower ΔV of 4.7 km/s compared to Bennus ΔV of 5.1 km/s. Ryugu, however, has a larger semi-major axis of 1.18 AU compared to Bennus 1.12 AU.[9] There is more information known about Bennu due to its selection for other asteroid-based missions; most notably the NASA OSIRIS-REx sample mission.[10] Hathor would utilize the information gathered from OSIRIS- REx to provide more detail regarding Bennu such as the contents Bennu contains.

With all these factors taken into consideration, it was decided that Bennu was the preferred asteroid. Although it requires more fuel to arrive at Bennu, the SLS booster rockets combined with the lander will be sufficient in enabling Hathor to transport the equipment required to mine Bennu. The OSIRIS-REx mission allows scientists to learn more about the asteroid and, therefore, allows the Hathor team to make a more informed decision about a landing place and long term feasibility. It is for these reasons in which Bennu is at a closer distance to Earth which saves fuel and in turn reduces the area needed for solar panels, that it is anticipated for Bennu to be rich in nonmetals, and is relatively close to earth compared to other asteroids that Bennu was selected as the target asteroid for the Hathor Excavator.

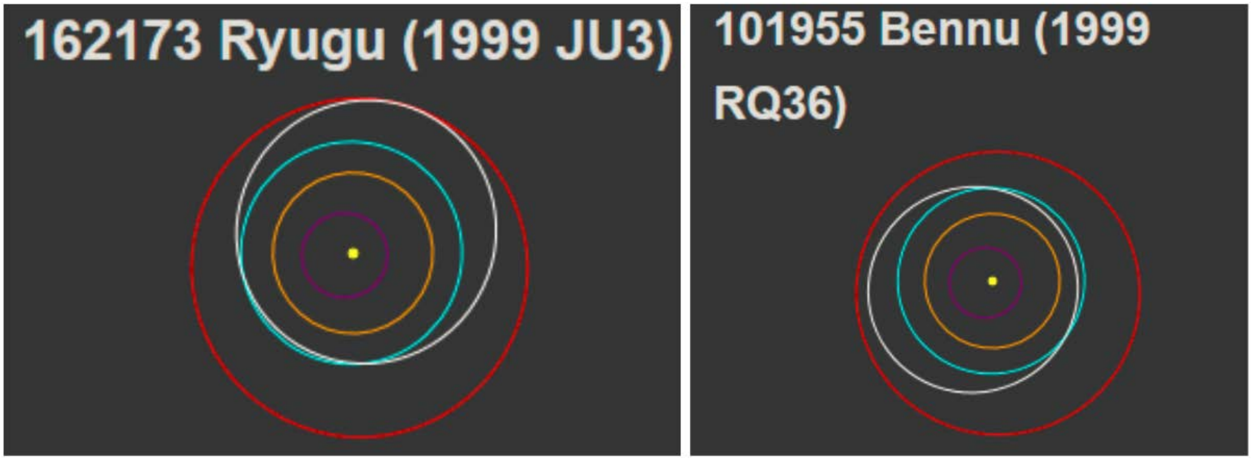

Figure 2. Orbital Patterns for Ryugu and Bennu. ***This figure shows the orbital patterns of the two final asteroids in the selection process.[9] For clarity, the asteroids' paths are in white, Earth is in teal, and Mars is in red.***

B. Orbital Trade Studies

Once Bennu was chosen as the objective for the mission, it was necessary to plot orbits for the potential trips to the asteroid. To do this, many aspects would come into play, one of them being the orbital path and dynamics the Hathor Excavator would need to undertake in order to arrive safely at its final destination. In order to plot the orbital path of Bennu in space, an application to help facilitate graphing the orbital paths was necessary. A code was found online from MathWorks which plots the orbits of all the planets in the solar system using the coding language MATLAB.[11] This code was then modified to enable a visual representation of Bennus and Earths orbits to determine an opportune launch window. The model included all the planets in the solar system, with the sun being the center body around which all other bodies revolve around. Bennu was also added to the model, as well as a spacecraft, whose position vectors will start in the Earths orbit. The code can be changed and updated depending on the date and time of potential launch. Once the chosen date is determined, the coordinates and vectors of each planet and object in the model are determined using the Johnson Space Centers Solar System Dynamics and Horizons Web Interface.[12] This application gives the position and velocity vectors for each planet and object when a date is inputted.

In order to choose the date and time of potential launch, it was evident that the launch needs to occur when Bennu is in close proximity to the Earth so as to provide enough time and the proper amount of distance for the spacecrafts orbital path to align with Bennus. Accordingly, research was done into the close approach dates of Bennu to the Earth. The website and database found to best suit the needs of the project was Asterank, an online database with details on orbits and parameters sourced from the Minor Planet Center and NASA Jet Propulsion Laboratory.[9] From this website, orbital information concerning the close approach dates for Bennu was found and compiled into a concise table, shown below in Table 2.

The dates of close approach were then narrowed down further to account for the time frame that the mission will be in. Dates too close to the current year were disregarded as potential dates as they would not allow for a reasonable time window to build and plan the actual mission. Dates also too far in the future were disregarded as well as the mission plans to be conducted within the next 10 years while it remains relevant to the work being done with the SLS. These decisions then left the mission with a reasonable time frame of around seven years in the future, which allows for the necessary time required to prepare for launch and create the Hathor Excavator.

The dates chosen for close approach between Bennu and Earth are: August 25, 2023; June 2, 2024; and February 25, 2025. Since all the above dates were potential launch dates which would get Hathor to Bennu in a time span of around a year, the dates were all potential options. Ultimately a launch date of June 2, 2024 was chosen in order to allow the team a maximum amount of time to prepare for the launch, but also to give the mission a backup launch date of February 25, 2025 in case something were to go wrong in the mission.

The launch date of June 2, 2024 was then plotted in the MATLAB function previously described, as shown in Figure 3. This allows for the analysis of Hathors orbital path in comparison with Bennu. When

Table 2. Upcoming Approach Dates. ***Table containing the upcoming approach dates where Bennu and Earth come into close contact, including dates and distance of the close contact in both astronomical units and gigameters.***

Date	Distance
Sep 01, 2017	0.336 AU - 50.3 Gm
May 15, 2018	0.352 AU - 52.7 Gm
Aug 25, 2023	0.497 AU - 74.4 Gm
Jun 02, 2024	0.360 AU - 53.9 Gm
Feb 25, 2025	0.392 AU - 58.6 Gm
Jun 21, 2030	0.346 AU - 51.8 Gm
Feb 18, 2031	0.231 AU - 34.6 Gm
Jul 12, 2036	0.310 AU - 46.3 Gm
Feb 11, 2037	0.099 AU - 14.8 Gm

the two bodies come in close approach of each other the time for that orbital was recorded to serve as the approximate date for landing on Bennu.

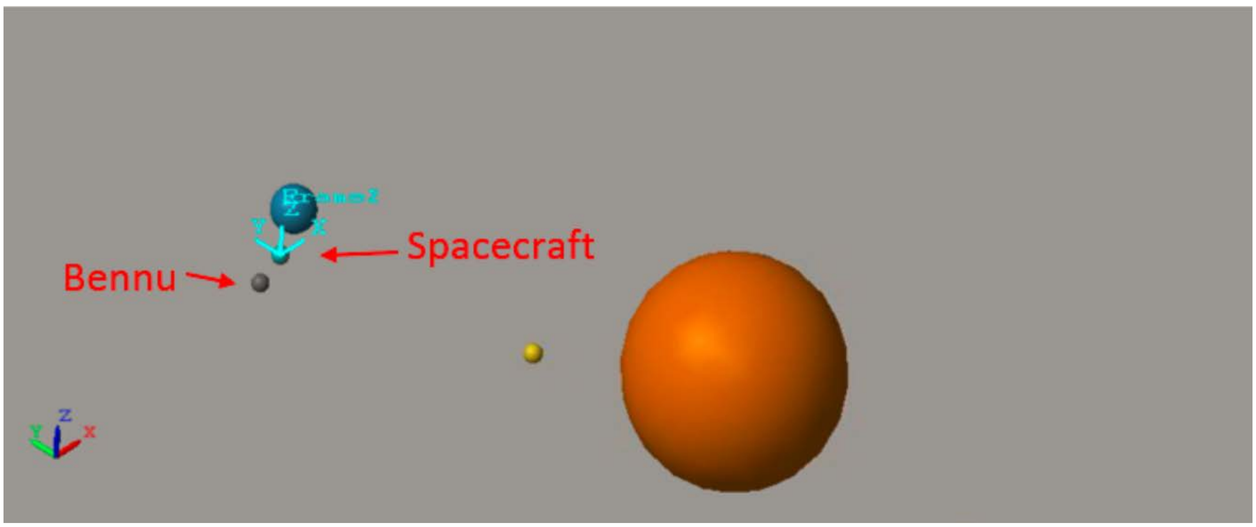

Figure 3. Orbital Path for June 2, 2024. ***This figure shows the orbital representation during the closest approach for the spacecraft and Bennu on June 2, 2024.***

The orbital path figure for June 2, 2024 shows the model for the timestep where Bennu and the spacecraft come into closest contact. This will be approximately 0.516 years from the date of launch, in November 2023.

Hathor will leave Earths atmosphere with a average velocity of 5.4 km/s. This velocity is used as an approximation from the Osiris Rex mission as both crafts will be of similar size and trajectory.[10] In order to land on Bennu, Hathor must use an array of small rocket thrusters to match the velocity of Bennu in its orbit around the Sun. It must also use the rocket thrusters to correct the path taken to get to Bennu as the orbital paths do not come into direct alignment as shown in Figure 3 above.

Hathor will finish mining on Bennu in February 2025 and will prepare the trip back to Earth. Hathor will leave Bennu with a low velocity and acceleration, evidencing a need for an an earth ejection burn to increase the average acceleration of Hathor to 0.32 m/s^2. This ejection burn will allow for Hathor to gain velocity to come into alignment with Earth to prepare for landing.

III. Hathor Excavator

A. Propulsion

Due to the nature of this mission there are a limited number of propulsion types to use. The SLS will send the system from Earth into a Bennu injection burn. The system will need to carry the propellant required to finish the approach to Bennu, Land on Bennu, and then return to Earths orbit with the additional mass of the collected materials. There are many options for propellants, including solid propellants, liquid propellants, and electric based propulsion, all of which had several pros and cons to consider.

Solid propellants are most commonly used in space launch vehicles due to their high reliability. Due to these solid propellant rockets being very simple with very few moving parts the likelihood of them failing is low. When designing these engines for launch the team would have to look at the trajectory they wish to take and design the grain of the propellant around that. The grain is the actual propellant inside the rocket, and how it is perforated will determine how intense the thrust will be at different times in the flight. The disadvantage for this mission is that we need to be able to control the spacecraft very carefully as it comes into a landing and be able to adjust the spacecrafts trajectory in case something goes awry. Solid propellants, however arent used very often in space vehicles; although they may be very reliable they cannot be stopped or varied once they are ignited.[13]

Liquid propellants on the other hand are generally used in space vehicles for everything from general propulsion in space, to orbital maneuvering, to reaction control systems. There are a couple different types of liquid propellants, cryogenic and hypergolic. The major advantage of liquid propellants is that they can be throttled. This is extremely important during space flight for adjusting trajectories and when attempting to land on surfaces in space, such as an asteroid. One of the disadvantages of liquid propellants is that they require a lot of extra space because you have to bring both the propellant and the oxidizer with you into space. Both of which normally have different storage requirements and will need more tanks to store them in, which adds both mass and limits space for other control and mission systems. The most common type of liquid propellant used for space vehicles is cryogenic propellants, these include liquid oxygen and liquid hydrogen (LOX/LH_2) and liquid oxygen and methane (LOX/methane). These systems are the most commonly mentioned in spacecraft propulsion but each have their own advantages and disadvantages. LOX/ LH_2 has a very high efficiency with an ISP about 30% higher than most rocket fuels, which is why it is most frequently used despite its very low density. The low density of LOX/ LH2 means that it will take a large amount of volume which translates to a large amount of the spacecraft being dedicated to it. LOX/methane on the other hand has a much higher density and doesnt have to be kept at nearly as low of a temperature (-162 °C as compared to hydrogens -253 °C) and has a comparable specific impulse (I_{sp})to LOX/ LH_2 which makes this a very desirable propellant. The downside is that it hasnt been tested extensively so how it will actually perform is unknown, but it is predicted to be used in future space missions. The other type of liquid propellant to examine is hypergolic propellants, which react on contact with each other. Hypergolics are tend to be easier to store than cryogenic propellants because they are not in a gaseous state at room temperatures. Because of this they do not require as much volume to store the needed amount of propellant mass for the mission. Hypergolics are mostly used with spacecraft control systems such as maneuvering systems, but they have been used for deep space missions or missions that are predicted to last several years. Another advantage to hypergolics is that they do not need an ignition source, this allows the propulsion system to be simple in design and reduce the chance of it failing. The main disadvantage to hypergolics is that they are very toxic and must be handled with extreme care. This makes them not as desirable of a propellant for a mission where the system will becoming into contact with humans.[14]

Electric propulsion is widely considered for many deep space missions due to its very high efficiency. One of the more popular propulsion devices is the Hall Thrusters, which can have a spacecraft reach an exhaust velocity of nearly 50,000 m/s. This along with the fact that electric propulsion doesnt require the large amount of propellant that is needed for conventional rocket systems make it a very appeasing option for space flight. The drawback of electric propulsion is that it normally has very low thrust values, which means it will take a long time for the spacecraft to perform a maneuver. For example, the Hall Thruster only gives about three newtons of force, which is why electric propulsion is not used for launch vehicles. Outside of deep space vehicles, electric propulsion is mostly used for orbital maintenance or other corrections because they dont require stored propellant and can be powered by the onboard solar panels easily.[15]

This mission will require high level of precision due the module having to approach and land on the surface of Bennu and will also have to have enough power to reach Bennu in a reasonable amount of time.

Even with these restrictions; the best choice currently for the main propulsion would be electric propulsion because of its high efficiency and reliability.The propulsion system for this mission will be based on the Ad Astra Rocket Companys Variable Specific Impulse Magnetoplasma Rocket (VASIMR). The VASIMR engine has a specific impulse of 4800 s and a thrust of 5.1 N when taking 200 kW of power[16].[17] Depending on how research goes in the next several years leading up to the full development of the SLS, this choice could change. If strides are made with LOX/methane based propellants then this could prove to be a better choice depending on how much propellant mass is expected to be used. Due to the low acceleration of electric propulsion, the system will need a different propulsion system when it approaches Bennu. A smaller cold gas system utilizing N2 would be able to provide the needed thrust to properly approach and land on Bennu. Orbital maintenance may be required during the course of this mission; a good choice of propulsion systems to use for this would be the same cold gas system. Due to the high simplicity of the system, cold gas is ideal for this. The main propulsion system would only be active during any orbital maintenance maneuver so the propellant mass would be very low.[17]

B. Power

As with any mission, minimizing the amount of mass on board a craft is essential. In order for this to stand true, Hathor needs a power source which provides a plethora of power yet is a reasonable weight. Adding an additional factor of traveling in space leaves limited options for sources of power such as: batteries, solar panels, and radioisotope thermoelectric generators (RTGs). When selecting which power to utilize for the mission it is necessary to keep in mind that mining hydrocarbons may produce some excess heat, which creates a high chance of expelling dust into the area surrounding the lander. Moreover, reliability is another crucial factor to be considered for the power on the mission as it must sustain the Hathor Excavator throughout the entire journey including while sampling Bennu to obtain the desired results.

Hathors power consumption has two distinct categories: flight and mining; the majority of the power will be consumed during the journey from Earth to Bennu. VASIMR needs 200 kW of power to run.[16] Once on Bennu, Hathor will need an estimated 1.6 W of power to move the acquisition arm, 471 W for the impeller, and 500 W for computers, communication, and any other power draw (For info on the acquisition arm and impeller, see IV-A and IV-B). This brings the power draw on Bennu to 972.6 W, just shy of 1 kW. Even though this is an estimate, it can be assumed that the mining power draw will at least be less than that necessary for VASIMR. It is a crucial factor that a power source is able to provide all needed power for transportation, besides while the craft is performing mining operations on Bennu.

Table 3. Trade Study of Power Sources

Power Source	Weight (kg)	Specific Power (W/kg)	Liability
Single Battery	9,221,050	100-190	safe
RTG (single)	55.9	5.367	moderate
Fission Reactor	N/A	N/A	unsafe
Solar Panel	2438	82.04	safe

Four sources of power were considered: batteries, radioisotope, nuclear fission, and solar. A number of parameters are compared in table 3.

The first option explored for a source of power was batteries. One type of battery that was an option for use on Hathor are lithium-ion batteries, which have a specific power anywhere in the range of 100 Wh/kg to 190 Wh/kg.[18] With the VASIMR requiring 200 kW of power, and an estimated travel time of one year, the battery would have to weigh 9,221,050 kg for just the flight alone. This is not feasible, so Hathor needs to have a means of generating electricity on the vehicle.

Nuclear energy was another power generating source analyzed . The goal, initially, was to equip Hathor with radioisotope thermoelectric generators (RTGs) as a result that RTGs generally produce low amounts power, below 0.3 kW.[19] This in turn would require a large number of RTGs to be attached to the vehicle yet due to their large volume and radiator fins, it creates a challenge to place an excess of them on the craft. NASA has explored more powerful nuclear options however, with research focused on Kilopower, a fission reactor that is recognized for producing kilowatts of power.[20] Nevertheless, radioactive isotopes are difficult to acquire and the possibility of encountering a launch pad failure excluded nuclear power sources from being considered for use.

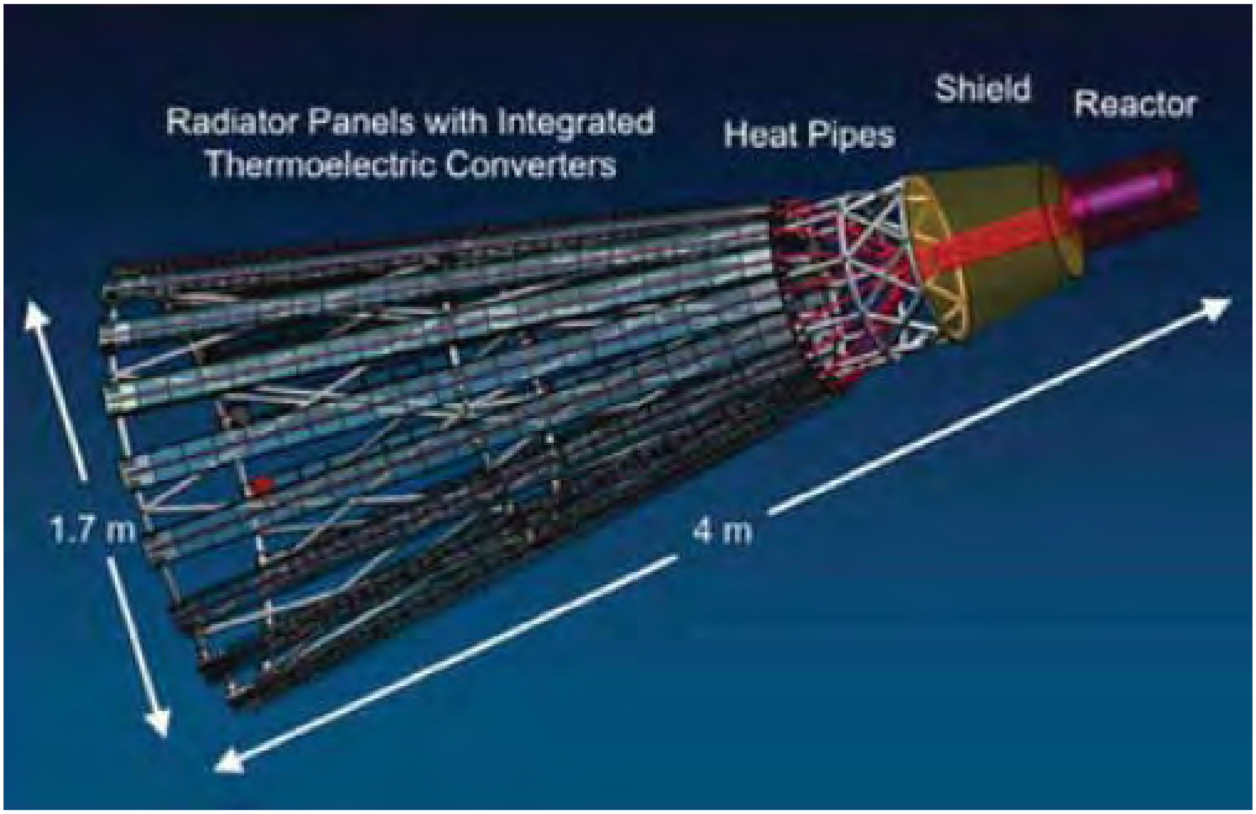

Figure 4. Concept model for Kilopower. ***This is one of the models from NASA's Kilopower article. It shows a potential shape and design for the system.***[20]

The final power source considered for possible use is solar power. Solar power is incredibly common in space exploration as it is able to generate electricity by taking in solar energy on the surface of a panel and store the excess power not used, for use in other systems on Hathor. The size of the solar panels can be determined using the inverse square law; the amount of solar energy at the furthest point from the sun (Bennus aphelion) is 748.662 W/m^2. Hence, the size of a solar panel would proportionately have to be 891 m^2. A solar panel wing would be broken up into two sections, one on each side of Hathor, with each side approximately 25 m long by 18 m tall. The panels will fold up lengthwise during launch, so they can be easily stored while in transit out of Earths atmosphere. As shown in the CAD model, the solar panels have triangular sections cut out of them in order to prevent damage from the propulsion systems exhaust. Although substantial in size, the factor of having the least amount of weight made for a compelling argument as to why solar panels should be used over other options explored. The solar panels will weigh a total of 2390 kg, a number obtained after estimating the average weight of the International Space Stations solar panels per square meter.[21] To take into consideration that the Suns rays with the panels may be interrupted which may interfere with potential mining at night, the Hathor Excavator will be equipped with a 100 kg lithium ion battery to provide the lander with a calculated number close to 5 kWh; therefore, the total mass would total to 2490 kg.

From these conclusions, solar energy was found to be the most efficient manner to supply power for Hathor. The solar panels that the Hathor Excavator will be equipped with, while they are not miniscule in size, are much lighter than other alternatives presented. The safety aspect of the mission is also a substantial factor throughout this mission to Bennu which is why solar panels were further considered as compared to nuclear power. Their large size coupled with their efficiency in converting natural resources into power is what allowed the decision to be deduced that solar panels will be the preferred method of providing power for the mission from start to end.

C. Structures

Hathor needs some casing in order to hold all of its components together and in order to hold it all up when under external and internal forces. The structure also dictates the location of all the components on-board the spacecraft.

Hathor is a dumbbell shape (as shown in figure 5) in order to locate everything effectively. The biggest constraint on shape and size of the spacecraft is the solar array, which are 18 m tall. The spacecraft needs to be at least that long so that it can reach Bennu on landing and also avoid damaging the solar panels when using its propulsion system. The spacecraft also needs to have a four meter wide on the bottom so that it has the greatest torque to work with when attaching to asteroid Bennu. A cylinder 4 m in diameter and 18 m tall is significantly larger than all the components Hathor needs so it is inviable. A dumbbell shape solves this problem by having two wide sections while adding extra length. One section of the dumbbell contains equipment pertaining to the propulsion system, while the other has equipment for asteroid mining operations. The spacecraft is just under 11 m in length, with the solar panels midpoint located near the propulsion end. The panels have a triangular section cut out of them so that the propulsion exhaust does not damage the array.

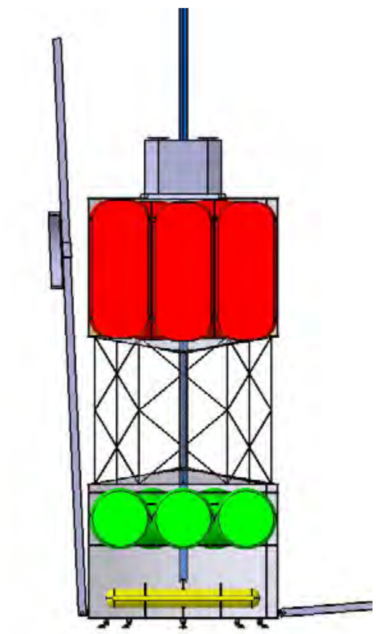

Figure 5. Hathor Cross-Section. ***This image depicts the cross-section for the body of the Hathor Excavator spacecraft. Note that the actual number of tanks recommended for the mission varies from that displayed in the CAD.***

External loads come from all thruster maneuvers, any interactions with Bennu, and loading and vibrations from launch. The greatest forces Hathor will face come from loads due to launch. According to the mission planners guide for the SLS,[22] the spacecraft will experience up to 3.5 gs during launch in the axial direction. Internal forces come from the pressurized containers, and all moving parts such as gases flowing through valves, the FORM arm and the FORM impeller. The greatest internal forces will come from the pressurization of the propellant tanks which will be up to 100 bars.

Typically, aluminum is used for the structure of spacecraft due to its high strength to weight ratio. The Hathor Excavator is not an exception and wouldnt benefit from stronger but heavier metals such as steel or titanium. Hathor will be primarily constructed out of Aluminum 7075, the strongest alloy of aluminum often used in aircraft. This particular alloy has a density of 2810 kilograms per cubic meter, a tensile yield strength of 503 MPa, a shear strength of 331 MPa, and a modulus of elasticity of 71.7 GPa.[23]

The structure of Hathor needs to be able to support 30 metric tons under 3.5 gs of acceleration or 1.03 MN of force. The propellant tanks are rounded cylinders roughly 1.5 m in diameter and 3.5 meters in length. Using the hoop stress of the tank as shown in equation (1), the aluminum walls must be at least 1.5 cm in thickness. To allow for a safety margin of 2.0 the axial force and tank thickness should be doubled. Table 4 describes the masses of all the propellant tanks on Hathor. Since the regolith tanks are not pressurized, they are rated to 5 bar. These tanks allow for 1.10 tonnes of nitrogen and 4.18 tonnes of argon to be stored. The tanks are mass inefficient but this is because the gases are low density and have no cryogenic systems to liquefy them due to their long-term storage.

$$\sigma_{hoop} = \frac{Pr}{t} \tag{1}$$

Table 4. Masses of Pressurized Tanks. ***The table shows the required masses to contain the needed propellants for the Hathor Excavator mission. The total mass is 9.2 metric tons.***

Tank	Thickness (m)	Volume (m^3)	Tank Mass (kg)	Num of Tanks	Total Mass (kg)
VASIMR Tank	0.03	0.548	1539.9	4	6159.5
Nitrogen Tank	0.03	0.212	595.7	5	2978.6
Regolith Tank	0.001	0.0067	18.83	5	94.135
Total					9232

The requirement for the axial structure can be determined by using Eulers critical load defined in equation (2) below.

$$P_{CR} = \frac{\pi^2 EI}{L_e^2} \tag{2}$$

During launch, the spacecraft held in the fairing can be thought of as having a fixed-free end condition. In that case the effective length, L_e is twice the actual length, 11 m. Using 2.06 MN for the critical load, and 71.7 GPa for the elastic modulus, the area moment of inertia of the spacecraft normal to the axial direction needs to be 0.0014 m^4. This requirement is not the critical factor for the two large parts of the dumbbell, however the truss and spine do need to take care of this factor. Without the truss, the center spine that connects the two sections would have to be 0.346 m in diameter and completely solid. With a truss of 1 centimeter in diameter 2 m from the centerline the moment of inertia requirement is already met, so the spine is a hollow cylinder with a 0.2 meter outer diameter and a 2 cm thickness. The truss and spine together weigh 131 kg.

The rest of the casing for Hathor is 1 cm in thickness. The total surface area of the casing, excluding the spine and including the support structures is 229 m^2, meaning 2.29 m^3 of material and 6,444 kg of material.

In total, 15.8 metric tons of aluminum are required to hold everything on Hathor together.

IV. Mining Operations

A. Asteroid Attachment

While undergoing collection operations, the Hathor Excavator will have to attach to asteroid Bennu. As Bennu only generates less than a milli-g of gravitational acceleration, the spacecraft cannot rely on gravity to keep it in place. Reaction forces generated by the regolith collector, the spacecrafts reaction control system, rotation of the solar panels and radiators, and internal movement of the collected regolith all contribute to moving or rotating the spacecraft relative to the surface of the asteroid, so the attachment mechanism must be strong enough to resist all of these forces.

Only a handful of missions have landed on low-gravity bodies such as asteroids so there isn't a large number of proven methods to rely on. Both the ongoing (at the time of this writing) OSIRIS-REx mission and the successful Hayabusa mission utilized only gravity in their contact with their respective bodies. However, as they collected samples and departed their asteroids in a matter of seconds; their method cannot apply to our mission. The Philae lander, part of the Rosetta mission, used multiple methods to land on the comet 67P/ChuryumovGerasimenko. It had shock absorbers in its legs, impact drills which screwed into the ice on impact, a harpoon to impale the ice, and a top mounted thruster to push it into the surface while landing. Unfortunately neither the harpoon, nor the thruster fired at its comet and the lander bounced off the surface before coming to rest roughly an hour later. In addition to having partially failed during the mission, these methods were designed to attach to a comet comprised of ices, not the rocks that Bennu presents to Hathor.

One method of particular interest has been tested on Earth, but not in a space environment. The current form of the Asteroid Redirect Mission plans to grab onto a boulder on an asteroid using a large number of tiny claws working together, called microspines. An existing robotic system known as LEMUR IIB, shown in figure 6, demonstrated that a single gripper (of 16 carriages carrying 256 microspines in total) given the optimum rock surface could hold up 281.4 N of force tangent to the surface 189.5 N normal to the surface and 113.2 N at a 45^o angle to the surface. Further specifics of microspines can be found in.[24] The surface of Bennu is a rubble pile, and is closest in tested terrain to bonded pumice and loose lava rock. Under these conditions, a single microspine gripper will hold 2.5 N normal to the surface, 20 N tangent to the surface, and 0.6 N at 45^o to the surface.

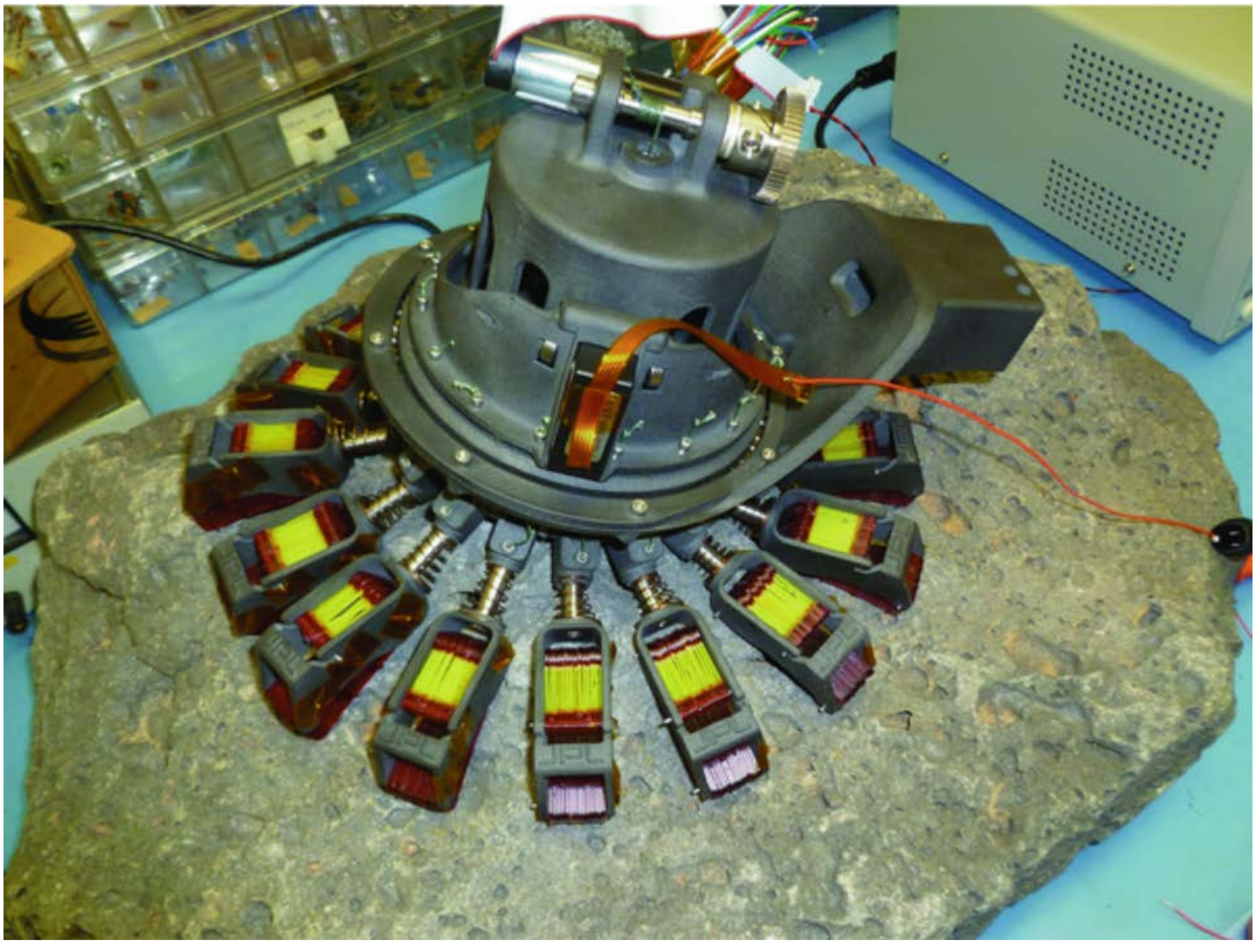

Figure 6. Mircrospine Prototype Photo.[24]

To determine how many grippers will be needed to assure a strong grip on the surface, the team considered the various forces that could push Hathor away from Bennu. All of the forces are summarized in figure 7. While rotating one of its collector arms downward to begin collecting, it induces a torque on the spacecraft pushing one end down into the surface and the other upwards. When rotating across the surface of Bennu (its rotation axis normal to the surface), the spacecraft will feel a torque relative to the surface. This torque is equal to the product of the arms moment of inertia and its angular acceleration. The mass and length of the FORM are estimated to be 400 kg and 15 m respectively giving it a moment of inertia of 30,000 kg*m^2. Torque can be minimized by slowing the rate of rotation, but it must still rotate fast enough to perform the mission in a timely manner. For example, if the arm takes 1 minute to rotate /2 radians the angular acceleration of the arm needs to be 1.745*10-3 rad/s^2. This would generate a torque of 52.36 Nm. Since the entire craft is 4 meters in diameter, a point force on the far side of the spacecraft would need to be

13.09 N to keep Hathor in static equilibrium. To keep Hathor stable, the arm will rotate at a maximum of 0.001 rad/s2, utilizing a motor that produces 30 Nm of torque. Keeping a safety factor of 2.0, a ring of 8 microspines around the outside edge of the craft would be sufficient.

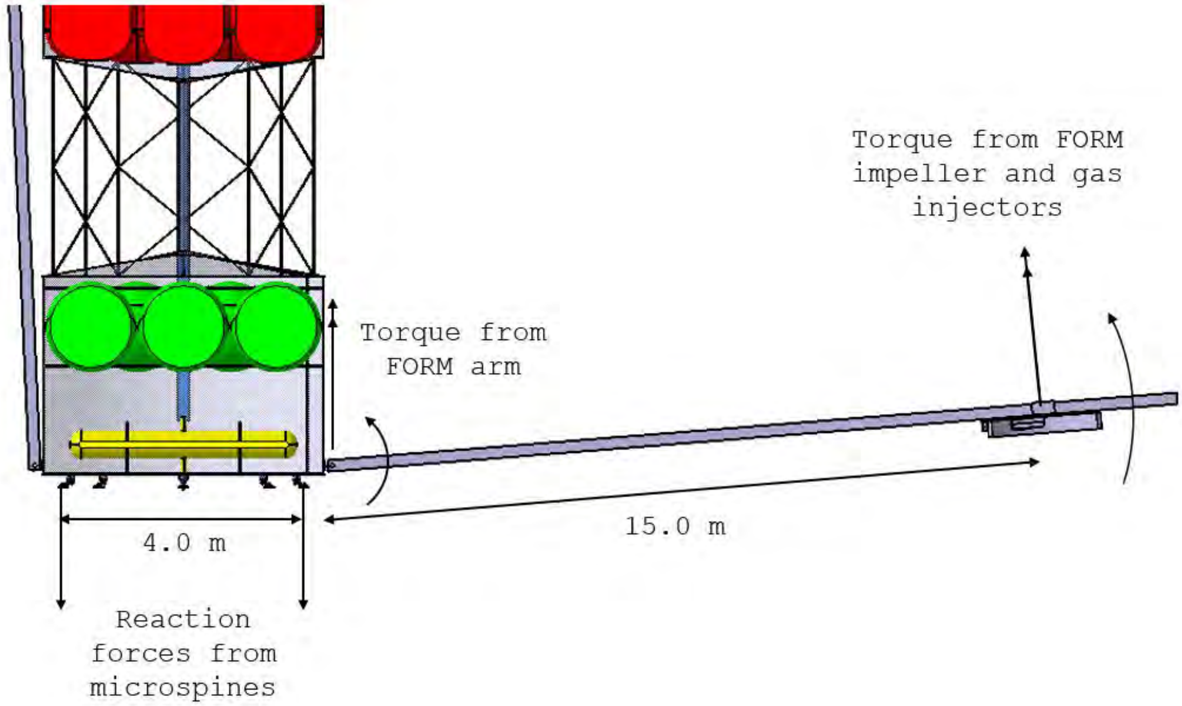

Figure 7. Summary of External Forces Affecting Microspines.

The second major source of force is the gas emission to collect asteroid regolith. While blasting dust and pebbles into the FORM, the gas functions similar to a small thruster pushing Hathor up and away from Bennu. From the tests in section IV B., 890 kPa of pressure will be used resulting in a force of 87 N from the four nozzles. This thrust can be more benign to the microspines by pointing the nozzles at a shallower angle to the asteroid surface, which lessens the component of force normal to the surface. This shallow angle is also desirable as it encourages the regolith to be pushed upwards more effectively. At 5° to the surface tangent, the total upwards force is 7.6 N. This force is easily distributed among the eight grippers. However, this force also causes a torque. At its worst case, the force is applied 15 meters away from the first microspine gripper. In this case, the ratio of average microspine normal force to the FORMs thrust is 19:16 meaning that each microspine gripper will experience roughly 9.0 N if the force is distributed equally. Since the microspines can handle 2.5 N normally, the safety factor for this scenario is 0.279.

The third and fourth major source of force comes from the impeller on the FORM and the motion of regolith moving within the pipes of the spacecraft. Since all of the momentum of the moving regolith is imparted by the impeller, forces generated by the moving regolith will always be less than those generated directly by the impeller. As with the motor that operates the FORM arm a maximum torque of 30 Nm is recommended for safe operation.

Other considerations to take into account include the possibility of bouncing on initial landing. The escape velocity on Bennu is as low as 0.18 meters per second at its surface, meaning very low velocities will put the spacecraft in danger, especially with its delicate solar arrays and radiators. Due to the time delay between Earth and Bennu, ranging from 2.2 to 19 minutes,[25] landing will have to be a completely autonomous process. Since the microspine grippers take a couple of seconds to firmly grip a surface, secondary measures will need to be put in place to aid landing. Cold gas thrusters, a subsystem of the RCS, will apply a small force to push the grippers into the surface of Bennu long enough to find purchase. These thrusters, along with the ones that will be used to aid its landing, will be placed at the far end of the spacecraft relative to Bennu in order to minimize the energy of the dust kicked up from the landing.

In order to control the landing, two sensors would be used. Accelerometers would be used to detect if the spacecraft is pushing against Bennu by checking if there is no acceleration on the spacecraft while the thrusters are on. Additionally, the accelerometers can determine if the spacecraft is resting on Bennu, by checking if the accelerometers register ten micro-g of Bennus gravity while all thrusters are off. Since the required sensitivity of the accelerometers is so tight, and since redundancy is desired, a secondary contact probe will be used to help verify landings. These would be similar to Apollos lunar surface sensing probe, and stick out roughly a meter below the grippers. On contact with the asteroid surface, these would register the touch and bend out of the way with minimal resistance. Should Hathor float away from the surface, the probes would bend back and register no more contact. Three of these sensors, placed equidistant around the bottom of the spacecraft would allow sufficient redundancy and allow measurement of the angle of approach just before touchdown.

Landing procedure on Bennu would be performed in 7 steps, starting from a 1 km parking orbit. These steps are illustrated in figure 8 and listed below:

1. Hathor performs a 0.1 m/s deorbit burn and rotates to be normal to the surface.
2. Hathor falls for over 4 hours towards the surface accelerating to 0.14 m/s.
3. Once contact probes detect the surface, the landing thrusters decelerate Hathor to 0.02 m/s
4. After a calculated period of time, thrusters reverse direction to push into Bennu at 1 milli-g. Simultaneously, the microspines begin to close.
5. After all grippers are closed, Hathor waits for 30 minutes to determine if it is attached.
6. Once attachment is confirmed each gripper opens and closes on the asteroid consecutively to strengthen grip.
7. On-board cameras transmit back images to Earth for human evaluation of attachment.

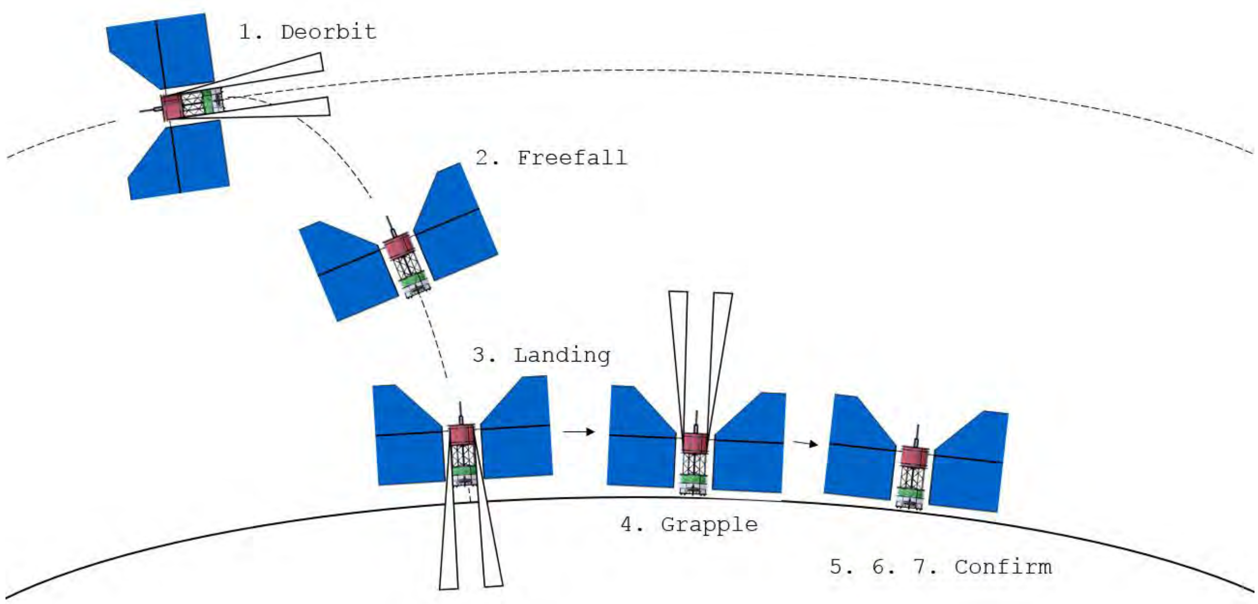

Figure 8. Landing Procedure for the Hathor Excavator.

Takeoff from Bennu is relatively easy. All microspine grippers release simultaneously and approximately five seconds later, the landing thrusters activate to accelerate the craft to 0.05 m/s. The small burn is to protect the spacecraft from dust blown up by the exhaust. Fifteen minutes later, and roughly 40 meters upwards, the thrusters fire again to accelerate the craft up to 0.5 m/s, well beyond escape velocity for Bennu. From there Hathor begins its trajectory back to Earth.

B. Regolith Acquisition

Design of the regolith acquisition method began by analysing Lockheed Martins existing Touch-and-Go Sample Arm Mechanism (TAGSAM) design (rendered in figure 9, which is aboard the Origins, Spectral

Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) mission.[26] As this device is being used on Bennu as well, it served as a fantastic starting point; however, the system was designed for small scale sample collection, and would not be suitable for larger collection operations. The proposed mission seeks to build on the design of the TAGSAM, incorporating a circular geometry and compressed gases in the collection apparatus to collect regolith.[26]

Many ideas were proposed for regolith questions. As previously mentioned, the first idea, upscaling the TAGSAM, was deemed impractical for the amount of material the mission was designed to acquire due mainly to the regolith being stored in the collection device, limiting sample size and processing capabilities. The design we chose was designed with transport to a storage/processing area in mind allowing for easier collection and processing of material.

Figure 9. OSIRIS-REx TAGSAM. ***A rendering of TAGSAM collecting regolith on Bennu.***

A bucket arm design similar to a terrestrial excavator was also proposed. Although this design would enable the mission to dig deeply into the asteroid, low gravity made this design appear unwieldy. Terrestrial excavators rely and gravitational force to stay anchored to the ground, a luxury in short supply on Bennu. Fears over the excavator arm toppling the spacecraft lead to its omission. Another concern is material being forcefully ejected by the excavator arm and being sent up in Bennus low gravity, possibly damaging the spacecraft or obscuring solar panels. If this design were to be used, significant consideration would have to be given to anchoring the spacecraft to the surface and material containment.

Another idea considered is the creation of a large bag-like structure attached to the surface and held up by centripetal force akin to a space elevator. Material would then by mined with a small, snow blower-like robot, thermal spalling, or even explosives. These methods would throw the material upward with sufficient velocity to be captured by the bag, which would funnel material to the spacecraft. This design was rejected due to the difficulty of anchoring the bag to the dusty, rubble-strewn surface of Bennu and the complexity of setup and operation. If these problems were solved, this method would promise efficient collection and easy return trajectories (as releasing the bag would kick the spacecraft up into a higher orbit).

Several other ideas were thrown around briefly, but none seemed sensible or effective. Magnets were briefly considered as an option, but when the mission was specified to be aimed at collection non-ferrous, volatile compounds, this design was thrown out. Another idea proposed taking advantage of Bennus close approaches to force Bennu to aerobrake in earths atmosphere and then enter a stable orbit. The timescale and high fuel cost of this mission alone were enough to rule out its possibility, not to mention that aiming a large asteroid at humanitys home planet is widely regarded as not a very prudent move. This option would however, provide an easy to study, pristine, if slightly singed, asteroid to study and mine within easy access of LEO.

After reviewing each concept the team created, a device was chosen that is optimal for the Hathor Excavator. The Fan Obtainment of Regolith Mechanism (FORM) is feasible as well as innovative from previous concepts already proposed and missions already occurring. It will be able to mine the half to full metric ton of asteroid rock from Bennu. The sampling unit consists of a sampling head and mobile arm four meters in total length. It utilizes a rotating fan and circulates high-pressured nitrogen gas to blast a contained area of asteroid for regolith acquisition.

When the craft reaches the specific mining site, FORM will contain a small area of surface on Bennu using a disk-shaped hood. The hood will seal the area so to decrease the amount of flying debris and excess gas during excavation. During excavation nitrogen gas is expelled from the top of the hood, causing particles will fly up towards the edge of the hood to be collected. Simultaneously the impeller will be circulating the gas and regolith particles. The hood is beneficial for the design because of the danger of flying debris to the spacecraft. The dust and light particles of the regolith can be easily disturbed and can fly off the surface at relatively fast speeds.[27] These fast moving particles can damage or obstruct parts of the craft and possibly jeopardize the mission. FORM will vacuum onto the surface of Bennu to keep extra regolith from endangering the craft and compromising the mission.

As stated above, FORM will blast the contained area with nitrogen gas. Nitrogen gas was chosen because of its elemental properties. Nitrogen gas is not flammable and is not extremely dense. Additionally, nitrogen is nonreactive and stable. Therefore, since it is not a dense gas, the storage of the gas will maximize the amount of extra weight the spacecraft can hold. It will overall reduce the tank volume and tank mass. The gas will be stored in canisters that can hold multiple attempts for regolith acquisition. When the area is blasted with the high-pressured gas, it will loosen light regolith for easy obtainment, while the fan within the sampling head will circulate the gas and regolith up the chamber to be stored back in a separate container.

After a successful obtainment attempt, the regolith will travel back up the tube where the gas was expelled and stored in a container for further inspection when the craft returns to low-earth orbit. It is important to note that the tubes must be smooth and bend minimally to minimize clogging.

Finally, the head of FORM is attached to a rotating arm. The arm will allow for the head to move to different locations on the surface of Bennu. The rotating arm will move around the stationary main part of the spacecraft. The sampling head will be in contact of the surface of Bennu for about thirty seconds for each obtainment attempt.

Oppositely, the loose regolith is also an advantage to the mission. The surface of Bennu is very dusty and contains light particles due to the carbonaceous-type asteroid. The C-type asteroid composition is composed of volatile compounds and water (in the form of ice).[28] The easily disrupted surface of Bennu creates less work needed to mine. If the sampling head was to drill into the surface of Bennu, that could create too much of a stirrup of debris and possibly fracture a section of surface of Bennu that would become a hazard to the spacecraft. Therefore, by simply blasting a portion of the surface and essentially blowing on the surface with a fan, the amount of regolith obtained is maximized and safely contained.

As stated earlier, this is similar to current mission being conducted by NASA already. The OSIRIS-REx mission utilizes a sampler that contacts the surface the asteroid Bennu for three to five seconds. FORM is innovative because it uses expelled gas and a fan contained with a disk head to obtain a significantly larger sample of regolith. The data obtained from the OSIRIS-REx mission will be beneficial to this mission. OSIRIS-REx will be able to inform more about the composition and surface condition of Bennu. The mission can be viewed as a follow-up to OSIRIS-REx to obtain a large enough sample to be mined for further use on Earth.[26]

When obtaining regolith, FORM will collect samples from the equatorial region of the asteroid Bennu. Based on radar images and analysis, this ridge suggests fine grained regolith materials. Mining this area can allow for less work, and more yield of sample.[28] The regolith condenses around the equator of Bennu due to the rotational movement and velocity of the asteroid.

FORM is not without issues. At the time of this writing, FORM is still an untested concept, so there are likely many issues to be discovered, and the cost of developing a fully functional version of the concept will likely be fairly high. Furthermore, the device is limited in the amount of regolith it can collect by the amount of gas carried in the system (although, future designs could allow collected minerals to be processed into gas) and may struggle to collect denser material like gravel. Additionally, there is a significant power

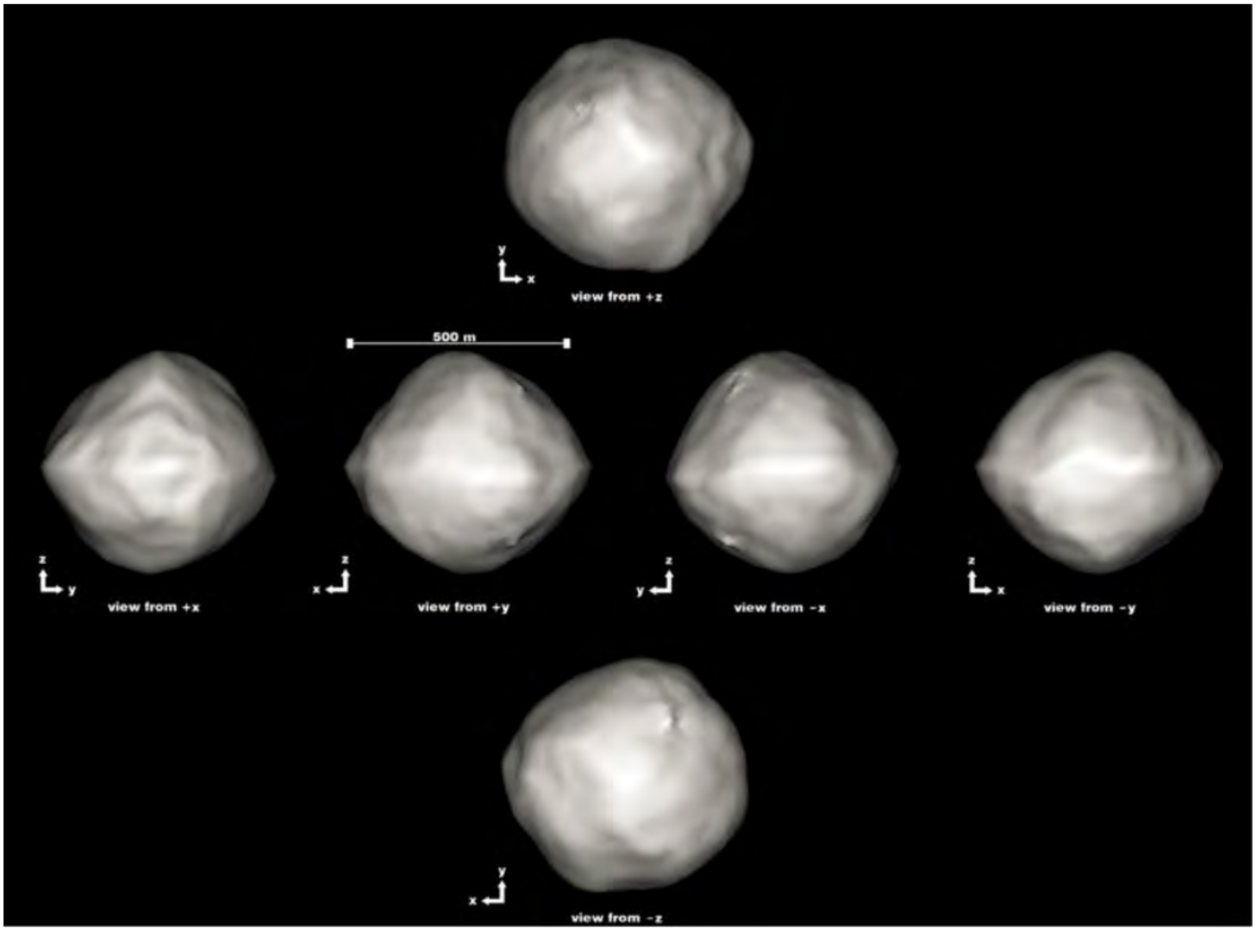

Figure 10. Equatorial Region Scan of Asteroid Bennu. ***This image shows the equatorial region of Bennu that is optimal for mining. It has been suggested that the loose regolith has collected around this area.***

draw for the motors need to drive the device and transport material.

Finally, and most importantly, the design calls for a large amount of dust to be sprayed upward. Although measures are taken to contain it, there is still a possibility of dust and debris being sprayed into unwanted areas and damaging components, obscuring solar panels, or jamming motors.

FORMs concept is optimal for the missions purpose. After much consideration for the purpose and dangers to the mission, as well as the economical and ethical protocol for the mission, FORM produces the most feasible and innovative design.

One important parameter in the design of FORM is the efficiency of the gas collector. The amount of stored nitrogen directly affects how much regolith the Hathor Excavator can collect. The theory of analyzing how a pressure wave will disrupt a loosely bonded collection of material is incredibly complex and not likely to yield reliable answers. Instead the team chose to create a prototype of FORM and gather empirical data on how effectively the device would function.

The test article can be divided up into three components as depicted in figure 11. They are the regolith collection chamber, the pneumatic machinery, and the sand testbed.

The regolith collection chamber is an open bottom cylinder, 500 mm in diameter and 150 mm in height. It is constructed of high density polyethylene due to its relative cheapness and smooth edges. This small scale test did not set out to determine how dust sticks to the walls and clogs the system over time so materials were only selected for structure and cost. Around the collection chamber are four injectors, each 90^{o} apart from its neighbor. These injectors are where the pressurized gas flows into the chamber and disrupts the surface material. Each injector creates roughly 22 N of force due to the internal pressure and injector area. The flight version of FORM may have differing injector designs that were tested for.

The pneumatic machinery is a collection of components that store pressurized air and distribute it to the four injectors. Air is pressurized via an air compressor and stores it within a small cylindrical pressure vessel. The pressure vessel is rated up to 100 psi which was the maximum pressure used for the series of tests. Passage to the injectors is blocked by a solenoid valve. The solenoid valve is connected to a simple breadboard circuit that allows air release at the push of a button. Finally, a component divides the air passing through the solenoid valve into four tubes that travel to the four injectors. Two pressure gages, one on the air compressor and one on the divider, allows measurement of the controlled pressures in the experiment. Using the ideal gas law, the 590 mL tank with a gage pressure of 100 psi contains an additional 4.7 g of pressurized air. If it were pressurized with pure nitrogen then the extra gas would weigh only 4.5 g.

The test bed is a small bed containing 18.2 lb (8.26 kg) of sand. As the sand is made of small particles, it more accurately simulates the rubble pile that Bennu is made up of. Additionally since Bennu has a gravitational force roughly five orders of magnitude less than Earth, moving smaller particles on Earth is more representative of moving larger particles under low gravity. During the tests, the sand was slightly wet, creating stronger bonds than what is expected of the regolith on Bennu.

The experiment consisted of three different tests, each simulating how the injectors could interact with the regolith. The first is the even surface test simulating a flat coating of material and the injectors firing parallel to that surface. It can also function as our control. The second test is the uneven surface test, which simulates a slightly hilly distribution of regolith. It can also simulate if the injectors were angled downward partially at the surface. The final test is the embedded injector test, which simulates the injectors being physically buried into the surface of the asteroid.

In each of these tests, the pneumatics are pressurized to 100 psi (50 and 75 psi are included in the even surface control test). The solenoid valve is released and the system is allowed to completely depressurize before closing the valve again. The quantity of sand blown into the air is captured using a video recording device. The process is repeated two times for each of the scenarios.

The control test on an even surface showed no lifted sand. At 100 psi some large pebbles experienced very minor surface disturbance, no upward movement. It would be safe to say that in this scenario, regolith acquisition would be negligible. During the uneven surface test, depicted in figure 12, an estimated 2.8 g of sand is blown upwards towards where the impeller would be. The amount of sand is increased to roughly 4.2 g in the embedded injector test as shown in figure 13. It is important to note that the repeated tests, which occurred after the first test without any change to the environment lifted close to no sand.

The environment on Earth creates results that are much less than what is expected on Bennu. Both the increased force of gravity and air resistance reduce the amount of sand that was launched upwards in comparison to the flight version of FORM. Additionally, our test bed had higher bonding forces between the sand grains due to its dampness, something we dont expect to see on Bennu. However, due to the atmosphere, air currents can be sustained carrying particles further than they would go in a vacuum. As a result it can be safe to assume that the system will be at least five times as effective on Bennu. Therefore in the best case scenario, a FORM of this size is expected to collect 21 g of regolith for every 4.5 g of nitrogen expended. This means that if the Hathor Excavator is to collect up to a metric ton of regolith, then it should hold 214 kg of nitrogen to guarantee that yield.

From these tests, a couple of procedures are recommended to ensure that all mining blasts have maximum yield. Firstly the FORM should aim to always embed its injectors into the asteroid surface. This can be accomplished by adding nozzles to the injectors that project in at a downward slope so that they may inject into the regolith like needles. Secondly, the FORM should make minor adjustments to its position after every gas firing. Doing so will always have the nozzles buried in new regolith allowing for maximum yield. Thirdly, the FORM can collect dust in the same area as the last firing so long as it finds a new place to embed its injectors.

C. Regolith Analysis and Storage

For this proposal, the idea to obtain a sample in order to analyze the contents on asteroid Bennu deemed a feasible task. The risks involved, in addition to the cost of recovering a sample and returning it to Earth to be analyzed, outweighed the risks of sample containment and analysis on Bennu. The true dilemma came when deciding in how to process the sample in order to analyze its contents. Out of a multitude of ways to determine what resides on the surface of Bennu, a Gamma Ray Spectrometer (GRS), pictured in Figure 14 and Figure 15 appeared the most effective way in which this task could be completed. Due to the fact this measuring technique does not need to simply scan the surface of Bennu compared to the other devices considered, including: an Alpha Particle X-Ray spectrometer (APXS), Chemistry and Mineralogy

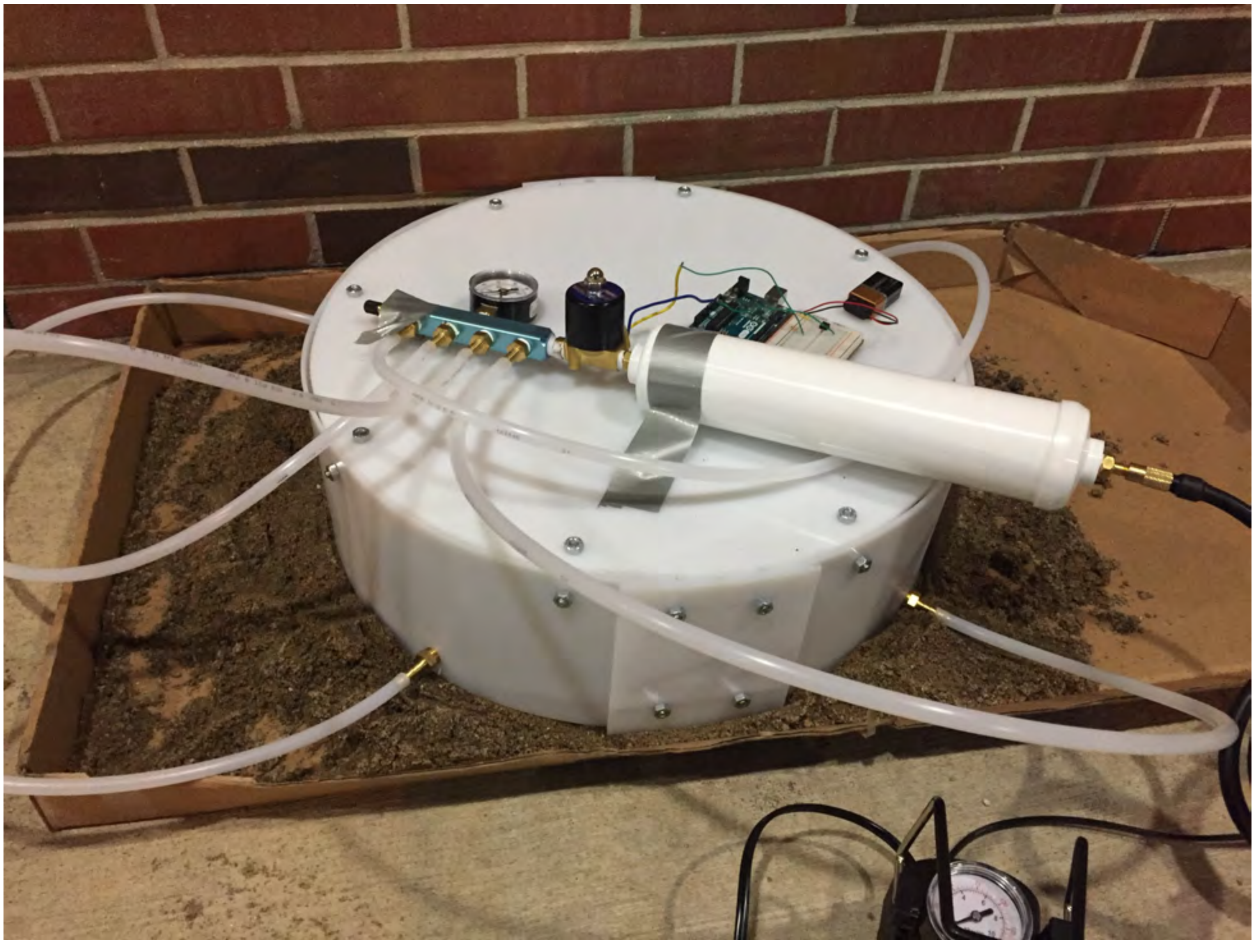

Figure 11. FORM Test Article. ***The FORM test article is composed of 3 major components: the cylindrical regolith collection chamber, the pneumatic machinery, and the sand testbed.***

instrument (CheMin), ChemCam, and Electrophoretic Separation; the GRS takes in a sample and analyzes it inside the body of the GRS. The GRS is also able to detect water in shallow subsurface depths; thus, this further enhanced the decision to use a GRS above all other types of processing systems.

A majority of the processes considered were based on the Mars Science Laboratory - Curiosity (MSL - Curiosity) which examined soil samples from Mars. Unlike the regolith collector on the Hathor Excavator, also known as FORM, Curiosity used each of the systems considered, simultaneously with each other to ensure thorough examination of the samples taken as well as analysis of different aspects of the soil, as evident in Figure 16. FORM will utilize the Gamma Ray Spectrometer to record data on the types of elements found on the surface of Bennu in addition to the concentrations of each element found.

The APXS, shown in Figure 17, was found to not be suitable for this design as it uses alpha particles and x-rays intermittently to examine the abundance of elements in rocks and soils.[29] Although the APXS is miniscule in size which benefits the design aspect of the Hathor Excavator, the APXS must be held in place for a long amount of time in order for the signal from the sample to be clearly determined. This would be disadvantageous to the Hathor Excavator as it plans to sweep across a vast range of the surface of Bennu to obtain a range of samples in order to obtain the clearest results of the contents Bennu is composed of. Another reason the APXS was not considered useful for this mission is in part due to its purpose used on the Mars Science Laboratory rover (MSL) which used the APXS to understand how the material formed and if it was later altered by wind, water, or ice,[29] and how it was used in conjunction with the CheMin and Dust Removal Tool. As the APXS and CheMin work together to analyze the soil on Mars surface, the CheMin identifies and measures the abundances of the minerals which can present scientists with information of environmental conditions that existed when they formed.[30] The advantage to the CheMin however, is that

Figure 12. Uneven Surface Test. ***This image depicts the test article during the uneven surface test conducted at 100 psi. Sand can be seen flying from the back left injector and unseen from the front right injector.***

it allows scientists to study the role that water had in forming minerals. In spite of the precise measurements both of these instruments provide, for this mission of mining an asteroid, it is not the main objective to determine how the soil formed, but what it contains, as this could lead to use of raw elements found for future missions.

A different instrument which was strongly considered due to its ease of operation is the ChemCam. Considering the ChemCam utilizes a laser system with multiple cameras, represented in Figure 18 and 19, and analyzes the data using a system of light wavelengths as pictured in Figure 20, to study the sample in question made it stand out amongst the other spectrometers considered. The ChemCam not only measures the abundance of elements present in the minerals, but can also recognize if ice and water are components within the soil. Although the ChemCam would be the best fit option for analyzing the components of the soil from farther away and not having a chance of destroying the components on the Hathor Excavator, what puts FORM ahead of other mineral analysis mechanisms is that it will not only obtain a sample from the surface of Bennu but provide data analysis of its contents right away.

In comparison to the entire craft, the GRS only has a mass of 30.5 kg and uses only 0.032 kW. In its entirety, the GRS is 46.8 cm by 53.4 cm by 60.4 cm[31] and is composed of two different parts to examine the sample: the neutron spectrometer and the high-energy neutron detector (HEND).[32] The neutron spectrometer allows scientists to measure the amount of hydrogen in shallow subsurfaces and as a result of hydrogen most likely being present in the form of water ice, the spectrometer is able to directly measure the amount of ice and how it changes.[33] The HEND can detect the composition of the subsurface of what the neutron spectrometer is not able to reach and analyze.[34] The size of the GRS compared to other instruments used to analyze a sample was another factor of why the GRS stood out more prominently.

The information that the GRS is able to record and the accuracy of measurements taken suggested it was the most advantageous to use on Hathor Excavator to complete this mission. The goal to recover a sample efficiently and analyze the contents to determine Bennus composition, without needing to return a sample to Earth, is what puts Hathor above other missions with its innovative design for acquisition, analysis, and expenditure.

V. Vehicle Health and Control

A. Communications

Bennu is over 1 AU away from the sun, so communication from the ground to the Hathor Excavator is tremendously important. Bennus short rotation cycle of only 4.2 hours poses a challenge when it comes to communication as does the distance between Bennu and Earth such that communication systems must be

Figure 13. Embedded Injector Test. ***This image shows the test article during the embedded injector test conducted at 100 psi. Significantly more sand can be seen flying from both the back left and back right injectors.***

strong and reliable. It is imperative the Hathor Excavator works semi-autonomously, meaning that it will have to receive and send information when it is facing Earth, and pre-programming will instruct the craft what to do when facing away from Earth; when communication is limited. With these requirements, the selection of communication systems was profoundly limited.

Ku and Ka-bands, which are often used in the military and currently on many other space missions, were the first modes of communication researched. These bands transmit a larger amount of data and can have smaller antennas, but they are more susceptible to interference due to their larger frequencies, and are crowded with pre-existing military and space signals. With the crowded nature of Ku and Ka bands, and these bands high susceptibility, this makes the transmission of research data harder.[35] Stability and openness are more important factors than antenna size and volume of data, which led to X-band waves being chosen as the mode of communication for the spacecraft. X-band waves have been used more recently, so the X-band is much less cluttered compared to other forms.[36] X-band waves are also less susceptible to interference, such as weather issues on Earth as well as dust and debris from the mining apparatus.[35][36] X-band waves will require a larger antenna and dish,but this wont be a problem, as the possible 5-10 kg gain from communications is easily offset by the 1000+ kg reduced when deciding Bennus power source.

Hathor will be able to receive data constantly while in flight with both a low-gain omnidirectional antenna, which can receive data from any direction but with low clarity, and a high-gain dish antenna, which requires a more direct stream of data but is much more clear because it is able to concentrate radio waves to one specific point. On the asteroid, the high-gain dish will take in information when the dish faces Earth. When it is facing away, the previous data will include instructions, so Hathor is not inactive during this time. The low-gain antenna, while on the asteroid, will be used for emergency use only, like the event of the high-gain dish failing. The combination of antenna types and radio band will be efficient in providing Hathor with its communication needs.

B. Thermal

Though power details the useful energy that flows in and out of the spacecraft, it doesnt take into account the total energy that enters or exits the system. This section will account for all the energy that enters and exits the Hathor Excavator.

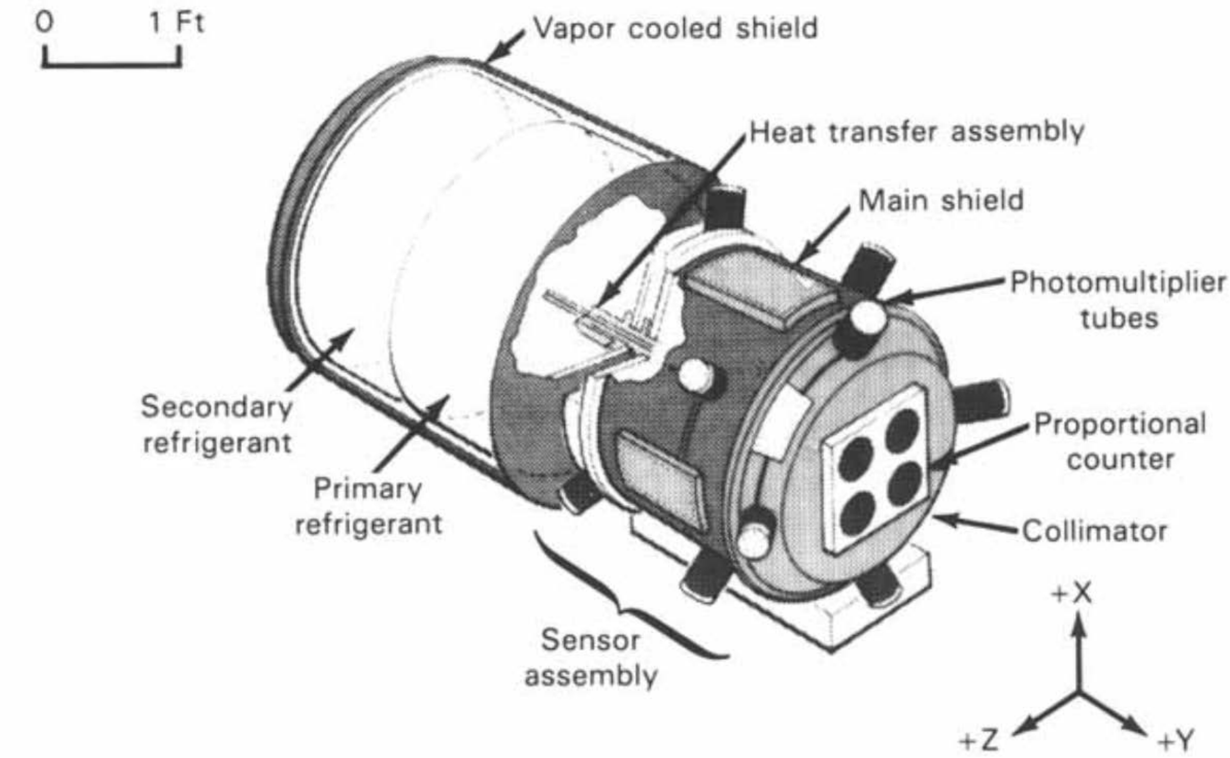

Figure 14. Full View of GRS

For the purposes of this analysis, the spacecraft is assumed to be in thermal equilibrium, simplifying the first law of thermodynamics down to equations (3) and (4).

$$Q_{in} + W_{in} = Q_{out} + W_{out} \tag{3}$$

$$Q_{conduction,in} + Q_{radiation,in} + W_{in} = Q_{conduction,out} + Q_{radiation,out} + W_{out} \tag{4}$$

There is only one method of energy acquisition and two main methods of energy release when the spacecraft is isolated in space. Hathor gains energy from solar radiation, and loses energy from thermal radiation and work done by the engine.

To calculate the total energy input due to solar radiation, three variables determine the energy over time: cross-sectional surface area, energy density of solar radiation, and the average reflectance of the spacecraft. Typically, the spacecraft has its solar panels completely extended and perpendicular to the suns light. This increases the cross-sectional area by 900 m^2, as determined by the power section of this paper. The body is cylindrical in shape so has two distinct cross-sections: that of the base, and that of the profile. The base has a cross-sectional area of 19.6 m^2 and the profile has a cross-sectional area of 38.3 m^2 as determined by the CAD concept. Assuming the body of the spacecraft has a polished metal surface, a fair description of gold foil radiation shields, the team assumed an albedo of roughly 0.81[37] for the body of the spacecraft. The team assumed that the solar panels are a black body, absorbing 100% of the light hitting them. Finally, the energy density of solar radiation varies based on distance from the sun. For our trajectory, the closest Hathor will be to the Earth is at Earth orbit, or 1 AU. It will be as far out as Bennus aphelion, or 1.36 AU. Using the same inverse square law calculation used in section III-B of this report, the team determined that the maximum solar energy density is 1366 W/m^2 and the minimum energy density is 748.7 W/m^2. With all of these variables, the team calculated the total power into the spacecraft in a variety of different configurations, as shown in table 5.

Energy leaves the spacecraft through either the propulsion system, or through thermal radiation. The VASIMR engine has an input of 200 kW and an efficiency of 60%. Therefore 120 kW of power leaves the

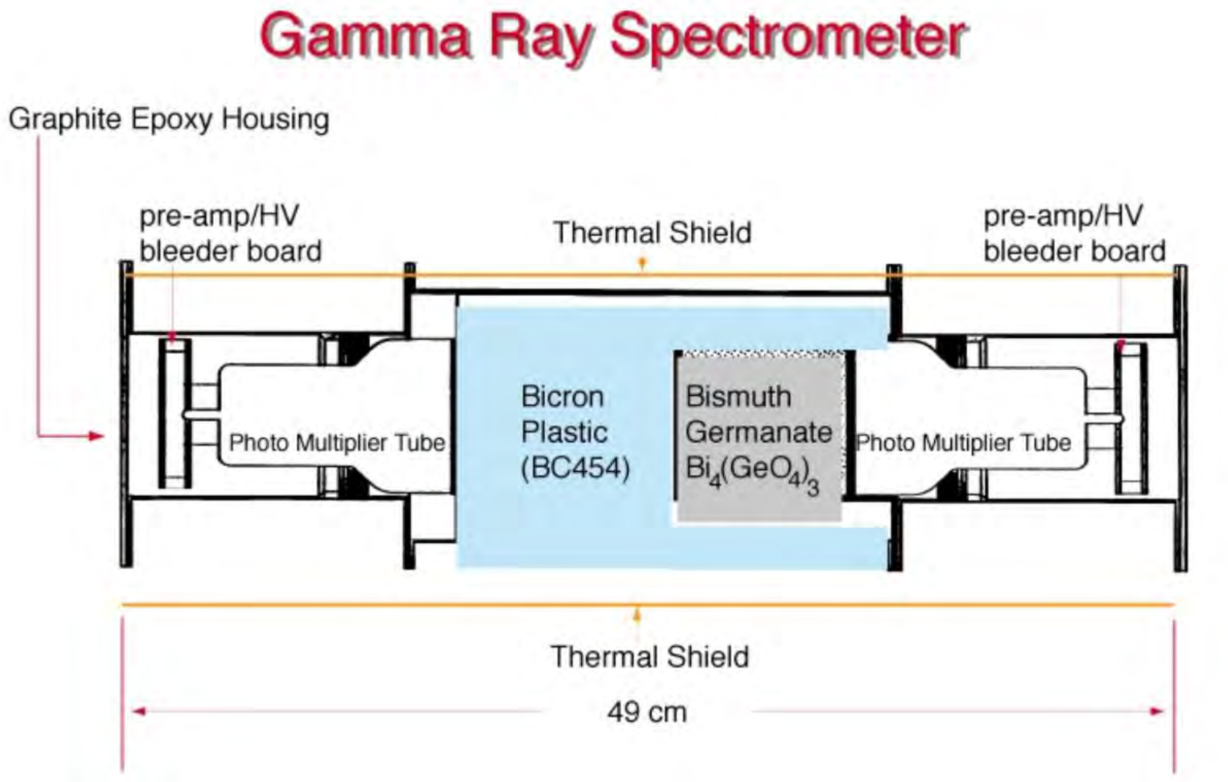

Figure 15. GRS Detailed Cross Section View

system through the exhaust when the engine is operating. Therefore all other excess power needs to be removed via thermal radiation. No matter the orientation of Hathor, the surface area for the purposes of thermal radiation remain the same. The spacecraft has a total surface area of 1997 m^2, 1800 m^2 coming from the solar arrays and 197 m^2 coming from the spacecraft body itself. Thermal power radiated by black-body radiation can be described using the Stefan-Boltzmann Law Eq. (5):

$$\frac{dQ}{dt} = \sigma A T^4 \tag{5}$$

Using table 5 for varying values of dQ/dt, the Stefan-Boltzmann constant for sigma and the previously calculated surface area for A, the team worked out the range of temperatures the spacecraft would operate at. In the orientation with minimal solar energy input, the average spacecraft temperature would be 81.9 K. If the engine was on in those conditions, the spacecraft could not be in thermodynamic equilibrium. On the other end of the spectrum, in the configuration with maximum solar input energy, Hathor would find thermal equilibrium at 324.0 K. The equilibrium temperature for all spacecraft orientations can be found in table 6.

From these values the team decided the particular modes of spacecraft orientation and the size of required radiators. Due to delicate electronic systems and the pressure inside the various propulsion tanks, the team decided to keep the spacecrafts operating temperature between 230 K and 280 K. In order to achieve this range at all times, Hathor should never fully turn its solar panels away from the sun, and slant its solar panels roughly 57^o from the normal to the sun when it is at 1 AU to remain cooler. At this angle, the solar panels still collect the necessary 200 kW of electrical power needed to run the engine but nothing more, reducing the amount of energy turned into heat. In this mode, the spacecraft should be between 278 K and 279 K depending on the orientation of the body. When at its furthest distance, so long as the solar panels remain normal to the suns light, Hathor should not cool down to dangerous temperatures. In this state, the spacecraft should also be between 278 K and 279 K.

If uniform temperature distribution is to be assumed then Hathor does not need thermal radiators, as the body of the spacecraft, particularly the solar panels, do that job for it. However, temperature is not

Table 5. Total Solar Power in Differing Spacecraft Scenarios. ***Depending on the orientation of the vehicle and its distance from the sun, the degree of power from the sun varies greatly.***

Vehicle Scenario	Power-in at 1 AU (kW)	Power-in at 1.36 AU (kW)
Maximum Cross-section	1,248	684
Minimum Cross-section	9.4	5.1
Maximum Solar Panels / Minimum Body	1,239	679
Minimum Solar Panels / Maximum Body	18.3	10.0
Slanted Solar Panels (200kW at 1 AU) / Maximum Body	685	375
Slanted Solar Panels (200kW at 1 AU) / Minimum Body	676	371

Table 6. Total Solar Power in Differing Spacecraft Scenarios. ***Depending on the orientation of the vehicle and its distance from the sun, the degree of power from the sun varies greatly.***

Vehicle Scenario	Temp at 1 AU (K)	Temp at 1.36 AU (K)
Maximum Cross-section	324.0	278.8
Minimum Cross-section	95.5	81.9
Maximum Solar Panels / Minimum Body	323.4	278.3
Minimum Solar Panels / Maximum Body	112.8	96.9
Slanted Solar Panels (200kW at 1 AU) / Maximum Body	278.9	239.9
Slanted Solar Panels (200kW at 1 AU) / Minimum Body	278.0	239.3

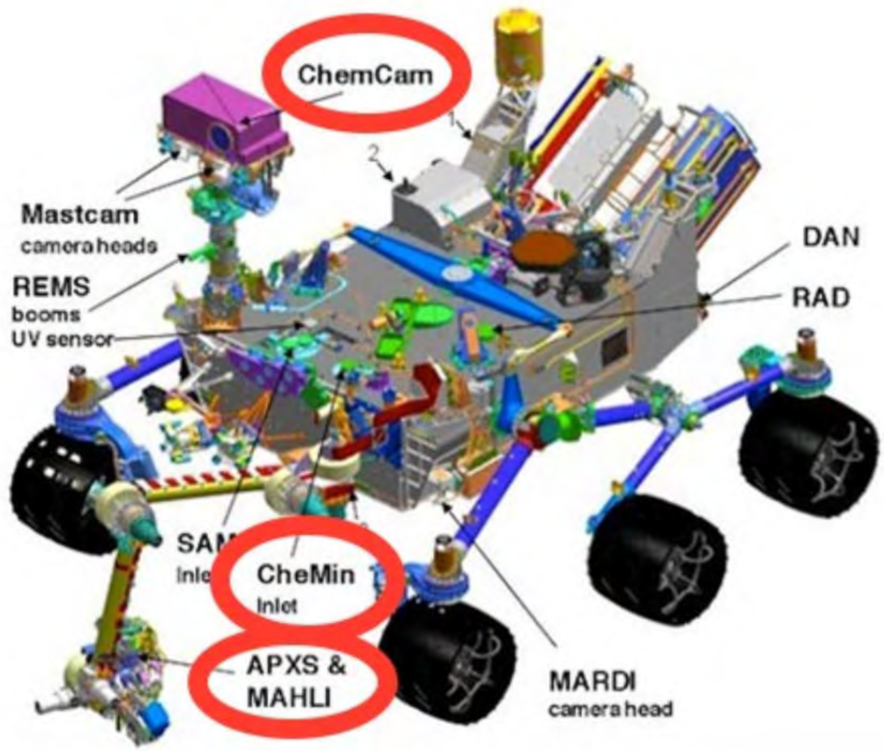

Figure 16. Spectrometers on MSL - Curiosity Considered for Hathor

uniformly distributed. In particular, the solar panels will be slightly cooler than the rest of the spacecraft due to 30% of the incoming energy being efficiently carried away as electrical current, and the VASIMR engine will be hotter when running due to the concentration of energy during operation.

In the case of the solar panels, there is little that can be done. If thermally isolated from the rest of the spacecraft, the solar panel would find an equilibrium temperature between 260 K and 261 K. This however, is within the range of acceptable temperature values for Hathor and therefore can be left alone.

The orientation of the VASIMR engine does not matter much. Though it can take in up to 3 kW of solar energy in the right orientation, that is trivial to the 80 kW of waste heat that is created by the engine operations. The engine itself only has an exposed surface area of roughly 6 m^2, and would therefore reach an equilibrium temperature of 696 K. This temperature is enough to seriously damage equipment in the engine so dedicated radiators need to be added to the engine. In order to reduce the equilibrium temperature down to 280 K, the radiators must be 230 m^2 in area.

Adding 230 m^2 of radiator changes the overall surface area of the spacecraft to 2227 m^2. However the changes are mostly insignificant. Equilibrium temperature for the whole spacecraft (assuming uniform temperature distribution) is reduced to between 270 K and 271 K in both modes. These temperatures are acceptable, and are the operating temperatures that all components on Hathor should be designed to work with.

The above analysis only applies to the spacecraft while it is in orbit, and in direct sunlight. While Hathor is interacting with Bennu, a couple of other factors change the variables in the thermodynamic analysis. Firstly, while on the surface of Bennu, Hathor is now able to exchange heat with the asteroid through thermal conduction. Secondly, Hathor will be periodically taken out of sunlight due to the rotation of the Bennu.

First the thermal conduction of Bennu is calculated. Bennu itself is in thermodynamic equilibrium while in orbit around the sun. Unlike Hathor, Bennu is roughly spherical in shape with a mean radius of 246 m,[27] and has a uniform albedo of 0.12.[27] Between the radii of the mission, Bennu has a uniform temperature of 279 K when at 1 AU and 240 K when at 1.36 AU. Once Hathor has been in contact with Bennu for a sufficient

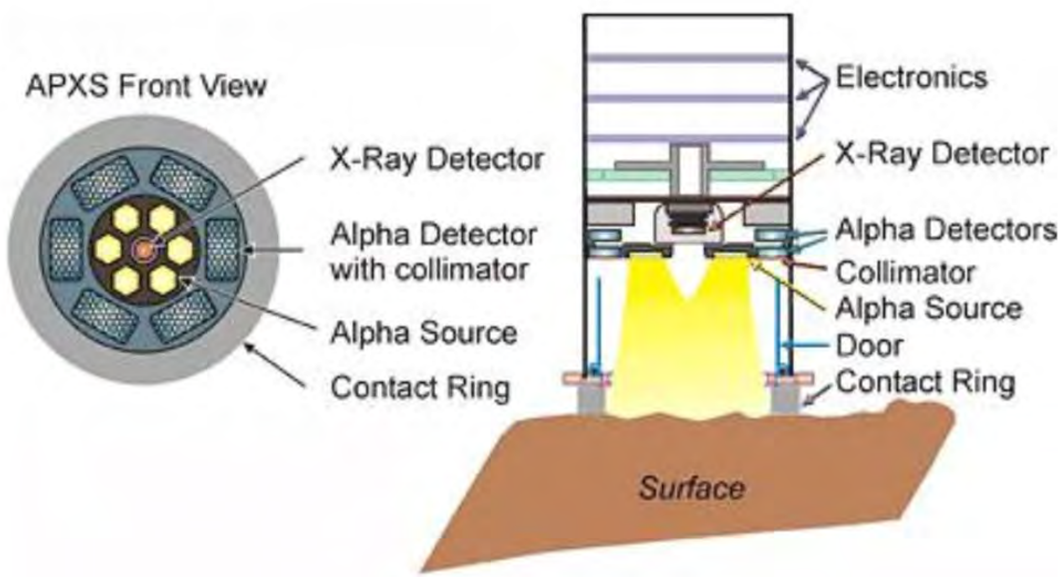

Figure 17. APXS Front and Side View

amount of time it will reach thermodynamic equilibrium with the asteroid and share its temperature as it fluctuates throughout the day and year. The spacecraft is recommended to land as close to the equator as possible to avoid the lowest temperatures on Bennu. Hathor is expected to feel temperature fluctuations between 250 K and 350 K throughout Bennus day.[38] The lowest temperatures are still within Hathors range of acceptability so no further actions need to be taken. On the hottest parts of the day, Hathor will angle its solar panels so they minimize sun exposure. Even if directly exposed to the sun, the solar panels are likely to stay at 260 K as previously specified. Should Hathor heat up further, then the panels can find the ideal angle to stay within the bounded temperature throughout Bennus day.

Secondly, the effect of Bennus shadow is calculated. Bennu rotates once per 4.288 hours.[9] While attached to the surface, Hathor is also subject to thermal conduction which is significantly higher than black body radiation. The results from above aptly cover this thermal scenario. While in low orbit around Bennu, Hathor can pass through the shadow of the asteroid for as long as 4000 seconds.[9] During this time, Hathor will cool down towards the cosmic background. The equation for black-body radiation power can be modified using the specific heat formula to get equation (6).

$$\frac{dT}{dt} = -\frac{\sigma A T^4}{cm} \tag{6}$$

Solving the differential equation for temperature T, substituting the Stefan-Boltzmann constant for sigma, the average specific heat capacity of 750 J/kg*K for c, the 30 metric ton mass for m, and an initial value of 270K at t=0 shows how the spacecraft will cool over time in darkness in equation (7).

$$T(t) = \frac{22300}{\sqrt[3]{160t + 567000}} \tag{7}$$

Using this model, Hathor will reach a minimum temperature of 209 K after passing through the shadow of Bennu. Since this value is beyond our ideal temperature range, Hathor must reduce the amount of heat it radiates or expend power to stay warm. As the 5 kWh battery onboard the spacecraft is too small to change the temperature by more than a single degree, Hathor must be able to retract its solar panels to conserve heat. The solar panels only need to retract to half their surface area. In doing so the spacecraft will reach only 234 K after spending 4000 seconds passing through the shadow of Bennu.

With these three scenarios covered, the team can be assured that the Hathor Excavator will be energy sufficient throughout its mission to Bennu.

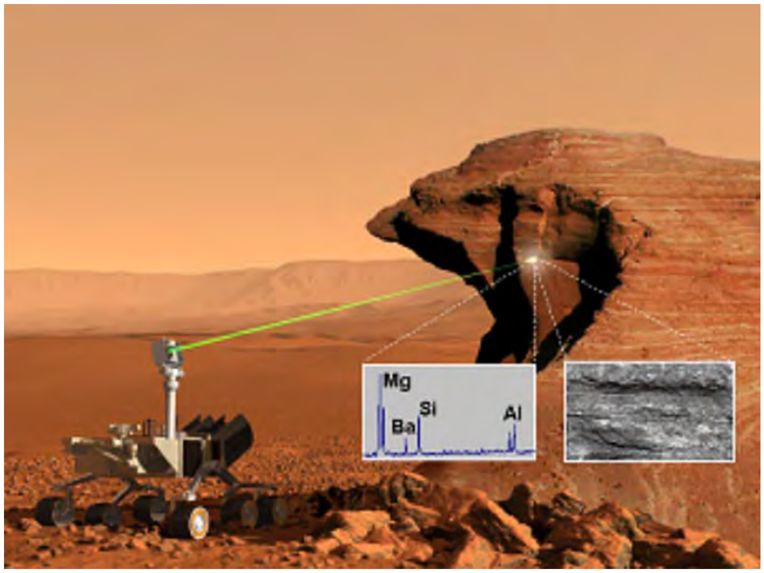

Figure 18. Example of ChemCam in Field

C. Failure Modes

With traveling outside of Earths orbit, come great risks for either manned or unmanned missions. Along with consideration for thermal protection against the harsh environment in space. Along with consideration for thermal protection, radiation protection must be put into place to ensure instruments on board are protected at all times during the journey to Bennu. Electronics must be radiation hardened and an outside shell on Hathor will provide Hathor with the security it requires. As previously mentioned in the communications section, Hathor will be use waves to communicate its data to and from Bennu to Earth. In spite of communications working smoothly a majority of the time, Hathor will store the data for the entire journey so that if any information got lost during the journey the Hathor Excavator will always have that data stored to transmit at another time. There is a possibly however, during this mission that Hathor will not be able to attach to Bennu correctly and or that there could be a possible failure during the obtainment of regolith on Bennu. Although there may be some possible chance of failure that could impact this mission greatly, the chance of those occurring are slim as calculations have been run entirely, and the mission has been reviewed a myriad of times.

VI. Costs

A. Legal

Laws regarding asteroid mining have, for the most part, not been defined. Although, a number of international laws and regulations have been proposed, only a limited number have been ratified, and confusion is compounded by numerous national laws which seek to govern space. The limited regulation and vague and occasionally conflicting nature of space law leaves the legality of asteroid mining rather nebulous. As the Hathor Excavator would be the first large scale asteroid mining operation in history, it would be setting a precedent for what can be done and how.

If NASA or a company is to launch from the United States (US), one must be concerned with US laws and regulations. The first hurdle one must overcome is securing an FAA launch permit. This is an involved process which requires the presentation of launch description, launch site description, launch vehicle description, payload description, trajectories, staging events, vehicle graphs, launch operator organization, organization summary, organization charts, office description, and safety functions among other things. For a more detailed look at the exact requirements see Federal Register Vol. 71 No. 165.[39]

The U.S. Commercial Space Launch Competitiveness Act, which is likely related to the creation of this competition (see Sec 117), ensures executive support of the proposed mission as quoted below:

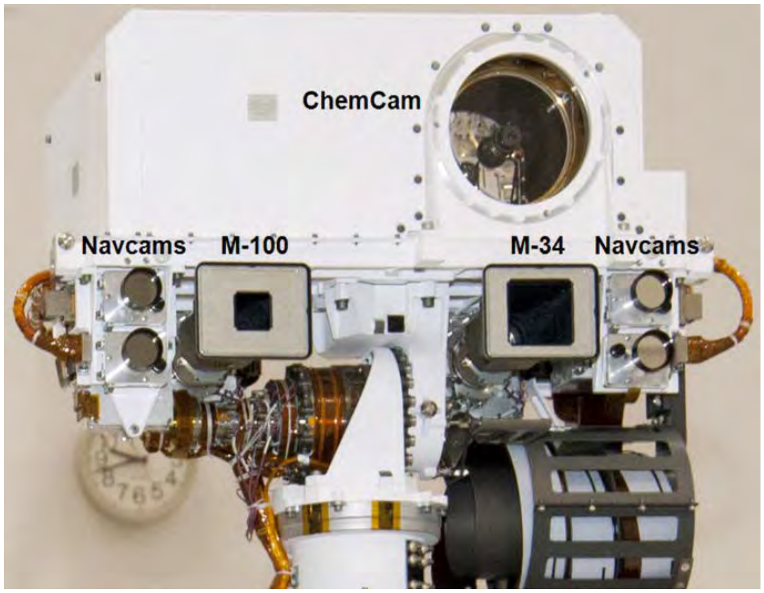

Figure 19. Labeled Subsections of a ChemCam

> (a) IN GENERAL.The President, acting through appropriate Federal agencies, shall (1) facilitate commercial exploration for and commercial recovery of space resources by United States citizens; (2) discourage government barriers to the development in the United States of economically viable, safe, and stable industries for commercial exploration for and commercial recovery of space resources in manners consistent with the international obligations of the United States; and (3) promote the right of United States citizens to engage in commercial exploration for and commercial recovery of space resources free from harmful interference, in accordance with the international obligations of the United States and subject to authorization and continuing supervision by the Federal Government. (U.S. Commercial Space Launch Competitiveness Act, Title IV - Space Resource Exploration and Utilization, Sec 402)[40]

This law essentially ensures that from the highest executive level, the US government is committed to promoting the exploration and development of space and space resource obtainment. This should help streamline the missions navigation of bureaucracy and provides national support on the international scene.

The main international law potential asteroid miners must be concerned with is the Outer Space Treaty as it has been ratified by all space-faring nations. This treaty outlines that the exploration and use of outer space and all celestial bodies, including Bennu, shall be carried out for the benefit and in the interests of all countries.[41] The proposed mission would be in line with this regulation as it seeks to develop techniques which could someday create abundant wealth for the people of Earth by means of asteroid mining. This mission could also be a stepping stone to refining fuel in space, ultimately driving down the cost of space travel significantly and opening it to a wider swath of people. Were the mission to bring back samples to earth, the mission plan would need to look into distributing wealth more equally (in accordance with the interest of all countries), but this is unprecedented legal territory and beyond the scope of the proposed mission plan. The outer space treaty further states that outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.[39] The proposed mission plan would be compliant with this regulation as no claim of sovereignty would be made by the launching country. However, it must be noted that the not all may agree with this interpretation of the treaty, and any launching organization must be prepared to defend their right to launch. NASA, with the support of the President of the United States of America, should have no issue with this as the Hathor mission is mainly scientific aimed at discovering the means by which asteroids could be mined. Future, private, commercial missions, though, could face stiffer opposition.

Of note, but no concern, is the Moon Treaty. As the United States of America, nor any space capable country, has ratified this treaty and the countries that have are few in number, this treaty does not pose any legal restrictions to launch, but it is worth noting its stance on the matter. The Moon Treaty, after

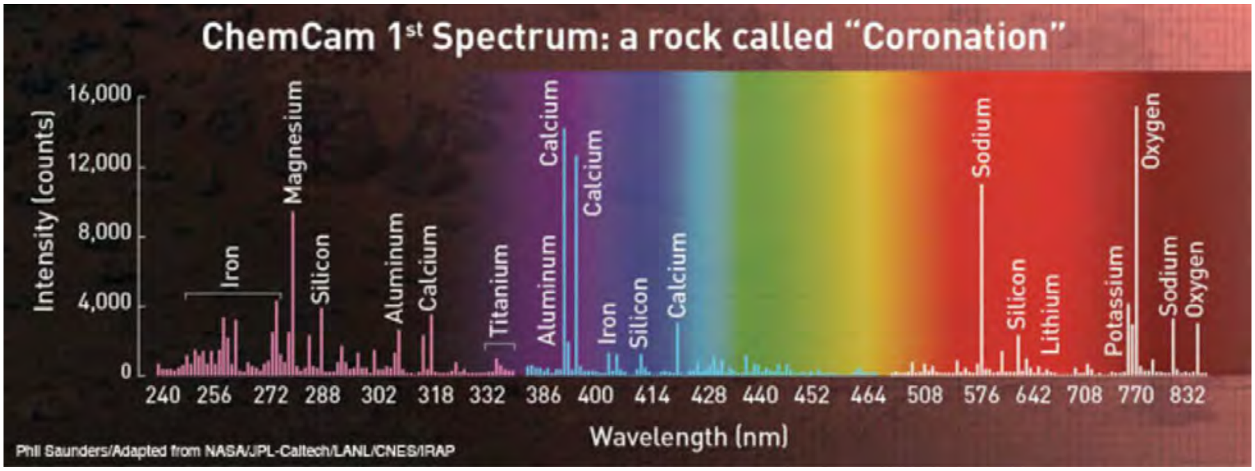

Figure 20. ChemCam Wavelength Spectrum Analysis

citing the moon and celestial bodies as the common heritage of mankind, states neither the surface nor the subsurface of the moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person.[42] This treaty clearly prohibits any extra-terrestrial mining and represents a sentiment shared by many that the resources beyond earth are not for any one person or subset of people to own. Although not binding, the mission must be concerned with the precedent set by its actions and be prepared for the logical extension of these actions such as mining on other asteroids or even the Moon.

Although Hathor is primarily a scientific mission, it aims to be a technological demonstration to market the idea of extraterrestrial mining to private companies. These companies would logically seek to profit from such endeavours, but what is profitable isnt always what is in the interest of all humankind. There is currently little to govern conduct in space with most missions operating on good faith principles. If Hathor or any similar mission does not take the utmost care to set a high standard of safety, responsibility, and sustainability, future missions could be dangerous, irresponsible, and unsustainable, potentially endangering earth or other spacecraft for decades.

B. Economic

The Hathor Excavator mission is a mission with the goal of exploration, discovery, and proof of concept in order to establish new possibilities for future missions. Due to the nature of this mission, and its goal of acquiring knowledge instead of immediate economic benefit, the mission has several economic components that need to be considered. Like any extraterrestrial mission, there is a cost attached to the Hathor Excavator mission, which is due to factors such as the cost of the materials and power/propulsion mechanisms, as well as regolith acquisition tools, and the labor and space required to take the mission from the design phase to the execution phase. However, the Hathor Excavator mission is not without its potential long term economic benefits, such as collecting valuable materials and reducing the cost of future space missions. One of the most significant costs of the Hathor Excavator mission is the cost of propulsion and power. The propulsion mechanisms this mission will employ are highly dependent on the research in the propulsion field that takes place between now and the time when the mission will be carried out. Due to this fact, it is difficult to properly project the economic costs associated with mission propulsion. However, by making the assumption that the mission will be propelled using methods identical or similar to current propulsion methods, it is possible make an approximation for the economic costs of propulsion for the Hathor Excavator. The current intended propulsion methods are standard liquid hydrogen and liquid oxygen with rocket engines, supplemented with ion propulsion. The estimated total mass of the craft is 30 metric tons, and the estimated mass of the craft plus the regolith gathered, which will be the total mass for the return trip, is 30.5 to 31 metric tons. The delta v required for a mission to Bennu is 5.096 km/s, and the mass of the craft combined with the delta v for Bennu and the escape velocity for the craft to escape the bounds of Earth give a required propulsion energy of 200 kWatts. The propulsion costs of the mission are moderately flexible due to possible advances in technology, however, the power mechanism is more definite, because the decision has already been made to use solar panels as the missions power source. As the power section demonstrates, the required area of solar panels our mission will need is 890.478 meters squared. The best method to determine the approximate cost for a solar panel of this size would be to find the cost of the International Space Space Stations solar panels per square meter, and multiply this by the area necessary for the mission. However, the cost of the solar panel used by the International Space Station is not information that is readily available. Instead, an estimate was determined starting from the cost of an 8 square meter solar panel most commonly used on homes. This cost is $464.36 per square meter,,[43] but the cost of an extraterrestrial grade solar panel would be considerably higher than the cost of an earth grade solar panel due to the harsh conditions of those found in space, so the cost per square meter for the Earth grade solar panel was multiplied by a factor of ten to account for the increase in cost. The resulting estimated cost of an extraterrestrial grade solar panel is $4643.63 per meter squared. The resulting cost of the mission solar panel can be multiplied by the area of the solar panels to yield an estimated power cost of $4,135,050. At this phase in the mission development process, a highly accurate power cost cannot be estimated, however, this is a reasonable estimate.

Another major factor in the cost of the mission is the cost of the vehicle, which will have an estimated mass of 31.5 metric tons. It is impossible to know exactly how much the vehicle will cost at this stage in the design process, however, using the cost of other vehicles and the relative mass of the Hathor Excavator vehicle, the Hathor Excavator vehicle cost can be estimated. The mass of the Hathor Excavator vehicle can be compared to the masses of vehicles used on missions of similar complexity in order to estimate this cost. The United States OSIRIS-REx and Stardust missions are comparable both in mission goal and complexity. These missions had vehicles of masses 880kg, 385kg respectively.[44,45] Those missions also had costs of $800 million,[?] and $165.6 million.[44,45] By finding a logarithmic regression for these two missions and extrapolating, a rough estimate for the cost of the Hathor Excavator can be found. A logarithmic regression was chosen because the complexity of the mission contributes a large portion of the cost and increasing the mass of the spacecraft does not directly increase the complexity of the mission. This estimate is $3.5 billion. Like all the other portions of this mission, the current cost estimates leave room for alterations. In this case the estimate is likely quite high, because the complexity of the missions the Hathor Excavator is being compared to was comparable to the complexity of the Hathor Excavator, but their vehicle masses were significantly lower. This estimate assumes that cost is based primarily on vehicle mass, however, cost is also significantly based on mission complexity. Notwithstanding, the fact that this estimate is high gives the mission more budget flexibility than a low estimate would.

Due to the nature of the Hathor Excavator mission, there is a significant cost associated with it. However, there are also significant benefits that can be reaped from the mission. It has been determined that Bennu has several different valuable resources, both metals and hydrocarbons. Due to the fact that Bennu is classified as a B type asteroid, it is expected to be both a carbon rich and primitive asteroid, meaning that it will yield fairly pure and useful samples.[10] Iron, hydrogen, ammonia, and nitrogen all can be expected to be found on Bennu, and possibly returned with the mission.[9] The samples collected from the mission will not only advance scientific research, they will also prove that Bennu will be a profitable asteroid to visit. The OSIRIS-REx mission is intending to return at least two grams of sample,[46] while the Hathor Excavator mission intends to collect and analyze .5 to 1 metric ton. This is significantly more mass than the OSIRIS-REx mission, and will provide a significant amount of information on Bennus substances and their applications in future missions. In addition, after all the necessary tests have been performed on the returned sample, it could possibly be sold for profit, and could even been sold for more money than a sample of that material otherwise could, due to the exotic nature of its origins. Iron ore gathered on earth has been increasing in value since September 2016, and has almost reached $90 per metric ton.[47] The profit that can be made from mining Bennu has been estimated at $2.50 billion.[9] Ideally, some of the materials returned from the Hathor Excavator mission can be sold in order to begin tapping Bennus economic potential. However, even if this is impossible, the mission will have successfully opened the gateway and whetted the appetite for further mining in the future.

The economic profit that can be reaped from the Hathor Excavator mission has significant potential, however, it is impossible to ignore the wealth of potential that lies in the scientific advancement benefits this mission could bring about. For example, Dante Lauretta, the principal investigator of OSIRIS REx stated that the dark, black surface of Bennu points towards high concentrations of carbon, which she hopes will be in the form of organic material.[46] The iron, hydrogen, ammonia, and nitrogen[9] that Bennu is expected to contain could prove useful in generating rocket fuel for future missions. Bennu thus has the potential to serve as a mining platform or sort of extraterrestrial gas station for future space missions. It is impossible to predict the exact benefits that can be reaped from the Hathor Excavator mission, nonetheless, by offering the opportunity to study a near earth asteroid in more detail, as well as proving that a sample large enough to be useful can be collected and analyzed in depth this mission can provide future scientific benefits of unknown bounds.

VII. Conclusion

This concludes the mission proposal for the Hathor Excavator. The mission proposal sets forth a multitude of plausible design solutions for an asteroid mining demonstrator, and provides quantitative evaluations for the validity of each of the proposed solutions. Furthermore, the Hathor Excavator distinguishes itself from other mission proposals by exploring unique concepts to create a more effective mission. The proposed time frame for the Hathor Excavator provides enough flexibility for developments in the mission and in the launch vehicle while being timely enough for economic benefits to have an effect. Commercial interests are kept in mind by providing solutions that are not exclusive to government agencies such as nuclear power. A detailed legal and economic analysis quantify the feasibility and benefits that private sector faces in future missions of this type. The Hathor Excavator utilizes new technologies that will be critical to the development of space infrastructure. The use of an electromagnetic engine presents a stepping stone for greater in-space propulsion, and the advancement on existing asteroid sample-return collection technology presents a stepping stone to large volume asteroid mining. This new technology has undergone preliminary testing by the team to ensure that it can reach the sufficient technology readiness level by the time of the mission.

Appendix

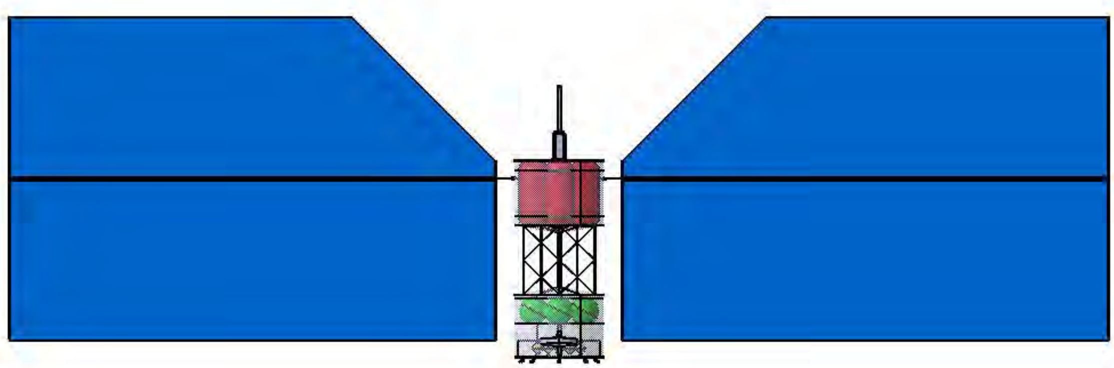

Figure 21. Front View of Hathor Excavator

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Table 7. Mass Requirement Breakdown by System

System	Component	Mass (kg)
Structure	Argon Tanks	6160
	Nitrogen Tanks	2979
	Regolith Tanks	94
	Casing	6575
Propulsion	Stored Argon	4180
	Stored Nitrogen	1100
	VASIMR Engine	620
Power	Solar Array	2390
	Battery	100
Mining	Primary FORM and arm	450
	Contingency FORM and arm	450
	GRS	31
	Collected Regolith	1000
Miscellaneous	Allowance	100
Total	Without Regolith	25229
	With Regolith	26229

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