Athena

Providing Insight into the History of the Universe....

Virginia Tech
Team
C.O.L.B.E.R.T.

Eric Buckenmeyer
Josh Eggleston
Andrew Lyford
Katie Rybacki
Umair Surani
Kris Walbert

Faculty Advisor:
Dr. Kevin Shinpaugh

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Executive Summary

The American Institute for Aeronautics and Astronautics has provided a Request for Proposal which calls for a manned mission to a Near-Earth Object. It is the goal of Team COLBERT to respond to their request by providing a reusable system that can be implemented as a solid stepping stone for future manned trips to Mars and beyond. Despite Team COLBERT consisting of only students in Aerospace Engineering, in order to achieve this feat, the team must employ the use of Systems Engineering. Tools and processes from Systems Engineering will provide quantitative and semi-quantitative tools for making design decisions and evaluating items such as budgets and schedules. This paper will provide an in-depth look at some of the Systems Engineering processes employed and will step through the design process of a Human Asteroid Exploration System.

Team COLBERT (from left): Josh Eggleston, Kris Walbert, Eric Buckenmeyer, Umair Surani, Andrew Lyford, Katie Rybacki

Applicable Documents

Document Title	Description of Document
2009-2010 AIAA Foundation Undergraduate Team Space Transportation Competition Request for Proposal (1)	Provides the problem definition and lists many of the mission requirements

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Nomenclature

NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
COLBERT	Close Object Landing By an Earth Research Team
HAES	Human Asteroid Exploration System
NEA	Near Earth Asteroid
ΔV	Delta Velocity
EVA	Extra-Vehicular Activity
AHP	Analytical Hierarchy Process
PT&E	Power, Thermal & Environment
CC&DH	Communication, Command & Data Handling
LEO	Low Earth Orbit
COTS	Commercial Off The Shelf
VASIMR	Variable Specific Impulse Magnetoplasma Rocket
VCR/MHD	Vapor Core Reactor coupled with a Magnetohydrodynamic power generator

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1 Introduction

1 1 Background

The United States has been the leader of manned spaceflight since 1962 when President Kennedy challenged NASA to reach the moon by the end of the decade The excitement over human spaceflight shifted in the 1980's to the Space Shuttle program, which was designed as a lifting rocket to put space stations into orbit rather than to explore new worlds like Kennedy's Apollo program The shuttle has been the focus for nearly three decades but now with an aging space shuttle fleet, a new direction for manned space flight must be developed

In 2009, a panel of 10 scientists was assembled to determine a solution to this problem The panel, known as the Augustine Commission, outlined viable options for the future of manned spaceflight with an end goal of sending humans to Mars A direct mission to Mars was found to be infeasible however, due to unproven technologies and mission designs The commission determined that before a manned mission to Mars could be pursued, it would be more practical to send manned missions to the Moon, the Martian moons, or a Near-Earth Object (NEO) (2) The goal of this project is to develop a preliminary design for a mission to a NEO This project will serve as a stepping-stone for a future manned mission to Mars and will help to extend humankind's knowledge of the solar system

1 2 Problem Definition

The American Institute for Aeronautics and Astronautics (AIAA) released a Request for Proposal (RFP) detailing their desire for a manned excursion to a NEO It is the mission of Virginia Tech's Team COLBERT (Close Object Landing by Earth Research Team) to respond to the RFP and develop a Human Asteroid Exploration System (HAES)

According to AIAA, a realistic mission to a NEO would have the following objectives The HAES must be capable of transporting two or more astronauts to a Near Earth Asteroid (NEA) and have them return safely to Earth The mission and technology should be feasible for a mission timeline between the years 2018 to 2030 The HAES must provide all of the crew accommodations and life support systems for safe travel and it must be capable of human exploration of the asteroid surface as well as the observation of the asteroid with scientific equipment Additionally, the system must be capable of extracting and returning to Earth at least 100 kg of asteroid material

The target asteroid for the Athena mission as determined by Team COLBERT from a previous design process is 1991 JW This asteroid was chosen primarily due to its abundance of launch opportunities, its earthlike orbit, and its classification as a ‘ Potentially Hazardous NEO” (3) Lambert's problem was solved through an iterative process in order to optimize total mission ΔV for specified launch and arrival dates ΔV is the net change in velocity needed to enter a different orbit and therefore can be used as a gauge for mission feasibility by specifying the amount of propellant needed After performing the required calculations, the optimal ΔV was found to be 8 79 km/s which corresponds to Earth launch and arrival dates of September 28, 2027 and March 7, 2028, respectively Figure 1 shows the orbital diagram of 1991 JW with respect to the orbit of the Earth along with the arrival and departure dates

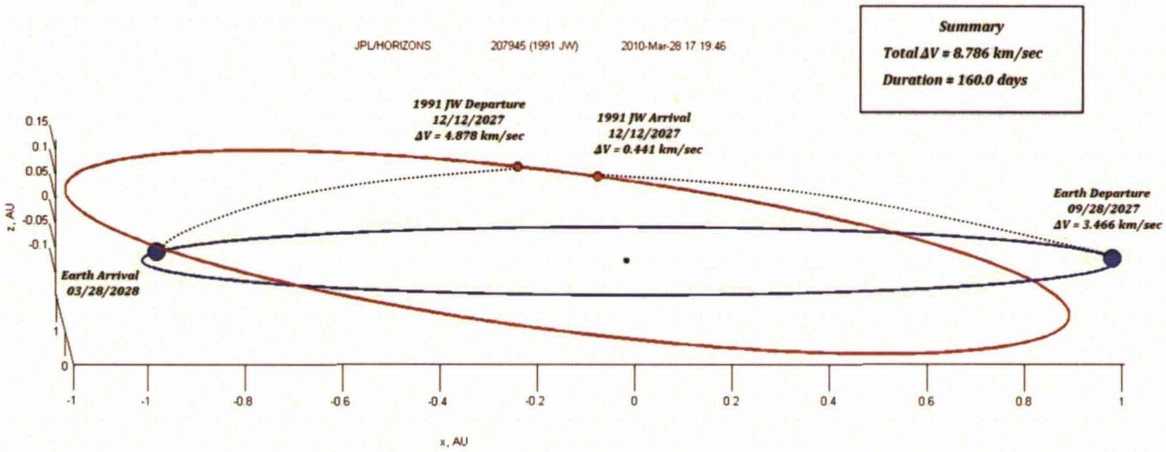

Figure 1: Orbital Diagram. This diagram shows the orbits of the Earth (blue) and 1991 JW (red) as well as the dates and ΔV requirements for the two arrivals and departures. The dotted black line corresponds to the transfer orbit that the the spacecraft will follow.

2. Systems Engineering Process

This section describes the systems engineering process implemented to develop the spacecraft design. It will highlight how the mission requirements were developed and validated. Subsequently, it will show how they were broken down into various systems and subsystems. Due to report length restrictions, the development of several major systems, such as the Attitude Determination System, was omitted.

2.1. Systems Engineering Process Planning

2.1.1. Major Products and Results from Process

The systems engineering process used for this design project will yield both a preliminary spacecraft design and mission profile. The complete design will include both the launch vehicles used and the spacecraft employed to transport crew and cargo to and from the asteroid. The mission profile will consist of dates and propulsion requirements for transporting the spacecraft to and from the asteroid.

2.1.2. Upper Level System Needs, Alterables, and Constraints

Based on the problem definition, the needs, alterables, and constraints of the upper level system are identified and listed in Table 1. The needs, alterables, and constraints were used as an initial step to determine the individual system requirements. The remainder of the section will discuss this process in a more fastidious manner.

Table 1 Needs, Alterables, and Constraints for the HAES This table identifies all relevant aspects of the mission as part of the first step in determining system requirements

Category	**Element**
Needs	To perform scientific research Data storage and transmission capability System to control asteroid landing Ability of astronauts to perform EVA s
Alterables	Asteroid selection Transfer orbit trajectory Propulsion system Launch vehicle selection Reusability of system Radiation and thermal protection systems Human life support systems Ground and space communication infrastructure Earth reentry/landing system Drilling technique Scientific analysis of asteroid Power system
Constraints	Mission must be completed by 2030 Must be capable of carrying at least 500 kg of cargo to asteroid Must carry at least 2 astronauts Must return at least 100 kg of asteroid sample

2 1 3 Resource Allocation

The design team consists of six Aerospace Engineering students at Virginia Tech Each student is the lead on a particular system and assists on other systems when necessary This type of structure ensures that there are no holes in communication and allows each system design to reach completion with no change in leadership, making the verification of requirements process simpler and less prone to errors In order for a system leader to gain more resources, he or she simply needed to ask the team manager for help

2 1 4 Verification Planning

In order to verify that all requirements are met, each system will be overseen by two other students specializing in different systems These students will ensure that all necessary requirements for the system, as outlined in the early stages of the design process, are completed in a satisfactory manner A benefit to using this style of verification process is that by having two students checking in on each system, the entire design team will have a better understanding of the entire project, thus minimizing communication errors and maximizing team efficiency

2.1.5. Objective Hierarchy Chart and Analytical Hierarchy Process

Figure 4 displays the Objective Hierarchy Chart developed for the design problem. The chart illustrates all major design factors and the criterion used to judge their effectiveness. There are five major upper level objectives in this design. They are Scientific Analysis, Technology Available, Performance, Cost and finally Safety. In the subsequent subsection, an analytical hierarchy process (AHP) will be implemented to judge the importance of each objective with respect to the others.

2.1.5.1. Analytical Hierarchy Process

An analytical hierarchy process was performed on the upper level objectives shown in the Objective Hierarchy Chart in Figure 4. The AHP is a tool that ranks the importance of each objective with respect to the others regarding importance to the mission. The process attempts to eliminate bias by allowing the user to compare only two objectives at a time (4). An AHP was also performed on the lower level objectives under each major category.

The chart shown in Figure 2 is the result of the AHP. These rankings show that the safety of the astronauts is the top priority of this mission followed by the amount of scientific analysis performed at the asteroid and the performance of the vehicle. Cost was second to last and the amount of information and technology available was the least important of the upper level objectives. This is appropriate because some of the technology that does not exist currently will be available in 2018 when the launch window opens.

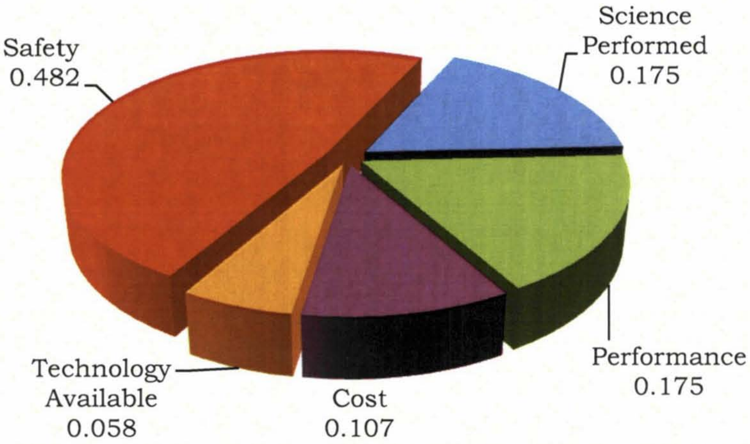

Figure 2: AHP Weighted Values. This graph shows the relative importance of each upper level objective to mission success. Safety received the highest relative importance score and the mission cost was least important to mission success.

The AHP results from the lower level objectives are shown in Table 2. The most important lower level objectives are the system's ability to adapt to the asteroid's environment, the launch cost and the system reliability. Mars capability was ranked third under the performance objective; this measures the system's ability to carry over to a Mars mission which is one of the major goals for a manned flight to a NEO. These rankings provided guidance for the trade studies that were performed throughout our design process because they established a minimally biased way of selecting the best design alternative for each system and subsystem.

Table 2: AHP Weights of Lower Level Objectives. These tables show the importance of the subobjectives relative to eachother.

Performance	
Objective	**Weight**
Adaptation Ability	0.513
Time Usage	0.149
Mars Capability	0.143
Power Usage	0.099
Communcation Capability	0.055
Reusability	0.037

Cost	
Objective	Weight
Launch	0.696
Operation	0.231
Production	0.071

Safety	
Objective	Weight
Reliability	0.573
Radiation Efficiency	0.286
Thermal Efficiency	0.139

2.2. Functional Analysis and Allocation

Due to the complexity of the project, multiple functional divisions were formed to divide the workload into manageable pieces. The main functional divisions presented in this report are the Power System, Human Systems, Command, Communication and Data Handling (CC&DH), Mission Architecture, and Asteroid Analysis. These functional divisions are assigned tasks that satisfy the needs, alterables and constraints specified in the previous section. For example, the Power System functional division is responsible for deciding how to power the spacecraft and its propulsion system. The complete allocation of tasks to the functional divisions is displayed in Figure 5. Functional divisions omitted from this report because of length restrictions include the Attitude Determination and Control System, the Thermal System and the Radiation Protection System.

2.3. Requirements Analysis and Validation

This subsection will outline the design requirements for some of the major systems displayed in Figure 5. Interfaces between systems and subsystems are also presented below.

2.3.1. Asteroid Analysis

One of the primary objectives of the mission is to extract at least 100 kg of asteroid material. This requires obtaining measurements of the composition, size, shape, and spin characteristics of the asteroid. It will also be beneficial to map the asteroid's magnetic field in order to maximize the amount of scientific information gained from the mission.

There are several instruments on the spacecraft that will be used to meet the science requirements. In the event of an instrument malfunction, other instruments on board the spacecraft can take similar measurements ensuring the scientific success of the mission via redundancy.

Interfaces with other functional divisions are also essential to complete the mission objectives. For example, ΔV calculations for the entire mission can only be finalized when the time required to carry out science and sample extraction objectives is known. In addition, the instruments' dimensions are required to complete the spacecraft structure design and the power requirement for each instrument must be known in order to determine the amount of power required for this system.

2 3 2 Mission Architecture

2 3 2 1 Orbital Propulsion

The propulsion system has several key requirements that it must fulfill to ensure a successful mission The engine and fuel tanks must be sized to fit in the available launch vehicles and the system must be capable of transporting the spacecraft to the asteroid and back Finally, the engine must be efficient so that the fuel requirements are minimized

In order for the propulsion requirements to be met, several interfaces have to be made with other systems For example, the engine's fuel and power requirements depend on the mass of the overall spacecraft Because all systems contribute to the mass calculation, each group must provide mass estimates before the propulsion system can be fully designed The amount of fuel required for the mission is also dependent upon the ΔV provided by the orbital analysts The engine's power requirements will then be given to the power system to verify that the spacecraft will have adequate power for the engine

2 3 2 2 Launch Vehicle

The launch vehicle must meet several requirements First, the system must be capable of launching the spacecraft and therefore specific payload mass requirements must be met In addition to the mass considerations, the spacecraft must also fit inside of the launch vehicle's fairing Finally, if multiple launch vehicles are used, at least one must have a human rating as defined by NASA to launch the crew into space (5)

The launch vehicle system must interface with several other systems The spacecraft configuration system must provide information on the fairing dimensions needed for the launch vehicle All systems must provide their mass requirements so that the least expensive launch vehicle possibility can be selected The chosen launch vehicle will then dictate mass constraints to the remainder of the systems The human systems group must also provide information to guarantee the safety of the astronauts during launch

2 3 2 3 Spacecraft Configuration

The configuration of the spacecraft provides sizing information to all of the other systems This system receives input from all of the systems because their components must be properly incorporated into the spacecraft To accomplish this goal, the systems must provide accurate component size and mass information as well as the desired location of the component throughout the mission The launch vehicles' fairing sizes must also be given to ensure that the spacecraft structure can fit inside for transportation to Low Earth Orbit (LEO)

The configuration of the spacecraft is also dependent on the information provided by the orbital analysts with regard to the asteroid operations The configuration will require methods to bind the spacecraft to the asteroid so that the crew will be able to conduct EVA's and extract 100 kg of rock from the asteroid

2 3 3 Power System

The power system configuration and design is based on the power requirements of each system Once each system provides information about their power consumption, the power system can be sized to meet these requirements A key driver to the design of the power system is the propulsion system If a conventional propulsion system is used, then the power system can also be more conventional If the propulsion system is electric, however, a larger, more unconventional power system must be designed Another driver to the power system is the length of the mission and the need for redundancy In addition to providing power for the main spacecraft, if a separate landing vehicle is used for this mission, a separate power system must be designed to power the lander during its asteroid operations

2 3 4 Communications, Command, and Data Handling

The size and design of the CC&DH system is based on the amount of information that must be sent throughout the spacecraft and back to Earth The communication system must be able to transfer communications and data to and from the landing vehicle, spacecraft, and Earth at a continuous rate This system must not only be able to perform this function, but it also must send information at a high enough rate to allow for the quality of data required Lastly, a system of command computers must be designed to control the communication and data handling as well as interface with other systems, such as life support, to ensure the crew's safety and mission functionality

2 3 5 Human Systems and Safety

The health system must be capable of supporting a minimum of two astronauts with medical equipment and a proper exercise regimen Exercise machines will be necessary to prevent muscle atrophy and healing systems will be used to repair bone fractures It is also important to monitor the vital signs of the astronauts so that any problems can be quickly diagnosed and resolved Finally, a waste disposal system will be needed to avoid sickness or contamination onboard the spacecraft

The human systems will need to interface with the power system to determine how much power will be available for use This will drive the types of equipment that can be carried on board as well as the size and capability of the equipment Additionally, the exercise equipment is constrained by the spacecraft's interior dimensions and layout This requirement is therefore interfaced with the spacecraft configuration system Masses of the systems will also need to be reported to the launch vehicle system and to the Mission Architecture group for launch considerations The safety of the astronauts on this mission is paramount and therefore human systems will be fully redundant to minimize the possibility of total system failure

2 3 6 Reliability and Maintainability

The fact that the system is being designed for a manned mission requires every facet of the system to be reliable In order to achieve this, many critical systems will be redundant For example, the propulsion system will carry two main engines If one main engine fails, the mission trajectory and timeline will change, but the spacecraft will be able to return the crew to Earth

The spacecraft is being designed so that it can be reused several times just as the shuttle has been for the last thirty years This reusability is desired not because the AHP dictated reusability but because the launch cost was deemed important Having a system that can remain in LEO will significantly reduce future launch costs thus it is desirable A reusable system means that parts must be easily replaceable and it must be easily refueled The spacecraft will sit in LEO attached to the space station that is active during the course of its lifetime Here, the astronauts need to be able to replace thrusters and other devices so that they are not used past the extent of their operational lifetime The spacecraft fuel tanks are also being designed to be refueled or replaced with minimal effort from the astronauts

2 4 System Synthesis

2 4 1 Commercial off the Shelf (COTS) or Developmental Items

In this design, COTS products will be used whenever possible because they reduce development costs and their heritage can usually be traced, providing the engineers with more data to assess their reliability Items that must be developed include the spikes that will hold the spacecraft to the asteroid and the equipment used to keep the astronauts on the asteroid Neither of these systems have been used in previous missions and thus COTS products are unavailable Each developed item will need to undergo many years of testing to ensure that it is fully capable of functioning properly throughout the mission

2 4 2 Reuse

Team COLBERT has decided to design a reusable system because of its ability to bring the launch costs down Despite the abilities of many of the spacecraft systems to be used repeatedly, some systems will need to be replaced at certain intervals These intervals will be determined by the parts that comprise the system and whenever a parts lifetime has been reached, the astronauts will replace it before their next mission This will help to minimize the system risk

2 5 System Analysis and Control

2 5 1 Trade Studies

This subsection will provide some of the major trade studies that were performed to reach final decisions about which technology to further develop in the design process Over twenty separate trade studies have been performed throughout the design process but due to length restrictions on the report, they cannot all be included Major trade studies omitted from this report include decisions regarding the attitude determination system and the propulsion power system

2 5 1 1 Mission Architecture

The mission architecture describes the type of engine used for orbital propulsion and the manner in which the fuel is carried during the mission This trade study drove many of the mission design decisions thus the most time will be spent discussing it The first design alternative consists of carrying the entire fuel load with the spacecraft from LEO to the asteroid and back Another method is to launch a fuel depot on a low-energy transfer to the asteroid so that the spacecraft could refuel at the asteroid for its return trip This option reduces the amount of fuel needed by 39%, but it increases the complexity of the mission (6) A third architecture option is to use a new type of engine known as VASIMR This option would require the fuel to be launched with the spacecraft, but the low fuel consumption of the engine allows less fuel to be carried This engine is under development but will be available in advance of the 2027 launch date (7)

Table 3: Technical Data for Mission Architecture Trade Study. This data was obtained using standard propellant calculation procedures (6). The VASIMR engine has an advantage in its fuel consumption due to its high efficiency.

	Volume LH_2 (m^3)	Volume LO_2 (m^3)	Fuel Launch Cost (\$FY10)
Conventional Propulsion	1969	725	$\$3.03 \times 10^9$
Conventional Propulsion with Low-Energy Transfer	1402	516	$\$2.17 \times 10^9$
VASIMIR Engine	370	0 (no oxidizer required)	$\$2.06 \times 10^8$

Table 3 shows calculated values for volumes of liquid hydrogen and oxygen as well as the cost to ship this fuel into orbit. Due to mass and volume restrictions, all fuel will need to be launched separately from the spacecraft. In this model, a Falcon 9 was used as the launch vehicle but launch vehicle choice is unimportant because the costs are relative to each other. The volumes of hydrogen and oxygen required are high for both methods that implement conventional propulsion. A trade study was performed to determine the type of architecture to be further developed.

Table 4: Selection Matrix for Mission Architecture. This matrix used several important mission criterion to select VASIMR as the technology that should be further developed. VASIMR will maximize reusability and the system's ability to be used for Mars travel.

		Conventional		**Fuel Depot on Hohmann Transfer**		**VASIMR**	
Selection Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Reusability	0.086	1	.086	3	0.259	4	0.345
System Complexity	0.516	5	2.58	1	0.516	4	2.064
System Cost	0.071	2	0.143	3	0.214	4	0.285
Mars Capability	0.171	1	0.171	2	0.343	5	0.856
Critical Technology	0.154	4	0.619	4	0.619	2	0.309
Grand Total			3.60		1.95		3.83

Table 4 displays the results of a trade study performed for mission architecture. The VASIMR system obtained the highest score and was chosen for further development. This design requires the spacecraft to carry the least amount of fuel while providing more options for abort scenarios and ensuring the return of the astronauts. The system also requires the fewest number of launches and therefore the lowest launch cost. Finally, the system also provides a reusable engine option and serves as a better stepping-stone to sending a manned mission to Mars than conventional propulsion options.

2.5.1.2. Power System

The power system is reponsible for powering all of the systems of the crew capsule, lander, and propulsion system. Originally, five different power systems were considered. The first system would use solar photovoltaic panels to create power. The second system would use thermal energy from the sun to create power. The next systems use cesium in a radioisotope thermodynamic generator (RTG) to create heat which in turn creates power through a system of thermocouples. Lastly, hydrogen-oxygen fuel cells similar to those on the space shuttle were considered.

Table 5: Power Trade Study (8; 9; 10). This trade study found the H-O fuel cell to be the most applicable for the HAES mission success. Upon further analysis however, it was decided to implement both fuel cells and solar arrays for standard spacecraft power.

		Solar Photovoltaic		Solar Thermal Dynamic		Cesium RTG		H-O Fuel Cell	
Selection Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Safety	0.368	9	3.312	8	2.944	5	1.84	7	2.576
Reliability	0.296	6	1.776	7	2.072	10	2.96	9	2.664
Production Cost	0.078	2	0.156	2	0.156	10	0.78	10	0.78
Mass	0.072	8	0.576	6	0.432	3	0.216	5	0.36
Power Output	0.132	5	0.66	1	0.132	2	0.264	7	0.924
Reusability	0.054	4	0.216	5	0.27	3	0.162	6	0.324
Grand Total			6.696		6.006		6.222		7.628

From the trade study shown in Table 5 it was determined that H-O fuel cells would be used as the primary power source and solar panels would be used as back-up power as well as to create oxygen and hydrogen from the waste water through electrolysis. However, this design proved inadequate with the selection of a VASIMR engine. In order to produce the minimum power required for one engine, it was calculated that 36 of the space shuttles fuel cells or 3.5 km^2 of solar panels would be needed (9; 10). The only way to produce enough power would be to include a nuclear reactor in the power plant.

The final power design now consists of a Vapor Core Reactor coupled with a Magnetohydrodynamic power generator (VCR/MHD). This reactor, which will be housed in the service module, will provide power for the VASIMR engines, the lander when docked, and aid in heating the lander and crew capsule (11). In addition to the VCR/MHD, the original power system design (H-O fuel cells coupled with solar panels) will be used to provide power, water, and oxygen to the lander when on the asteroid.

2.5.1.3. Structural Configuration

The structural configuration determines the type of vehicle that will transport the crew to the asteroid and then back to LEO. This is the portion of the vehicle attached to the VASIMR engine, which was selected in the Mission Architecture section. The first possible configuration consists of a lander, crew capsule and an orbiter. The orbiter is a module that would house the crew throughout the mission. Another available configuration consists of simply a lander and the final option consists of both a lander and the crew capsule, which would remain, in the asteroid's orbit. For the latter two options, the crew would live primarily in the lander.

Table 6: Selection Matrix for Structural Configuration. This trade study selected the Lander with Crew Capsule to be the best configuration because it minimizes complexity and maximizes the systems ability to conduct scientific analysis.

		Orbiter + Lander + Crew Capsule		**Lander Only**		**Lander + Crew Capsule**	
Selection Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Structural Mass	0.074	1	0.074	5	0.369	4	0.295
System Complexity	0.421	2	0.841	5	2.103	4	1.683
Reliability	0.249	5	1.246	1	0.249	4	0.997
Mars Capability	0.086	3	0.258	2	0.172	3	0.258
Science Analysis	0.170	5	0.852	1	0.170	5	0.852
Grand Total			3.27		3.06		4.08

Table 6 displays the result of a trade study performed on structural configuration. The lander with a crew capsule configuration received the highest score and was chosen for further development. This design allows the astronauts to have two living spaces providing redundancy should one of the systems fail. The system also allows the scientific instruments attached to the crew capsule to perform analysis while the crew is on the surface of the asteroid. Figure 3 shows a picture of the lander in descent toward the asteroid and the orbiter flying near 1991 JW. The lander will house the crew throughout the vast majority of the mission. Figure 6 shows a close up view of the assembled spacecraft, which includes the lander, crew capsule, and propulsion system.

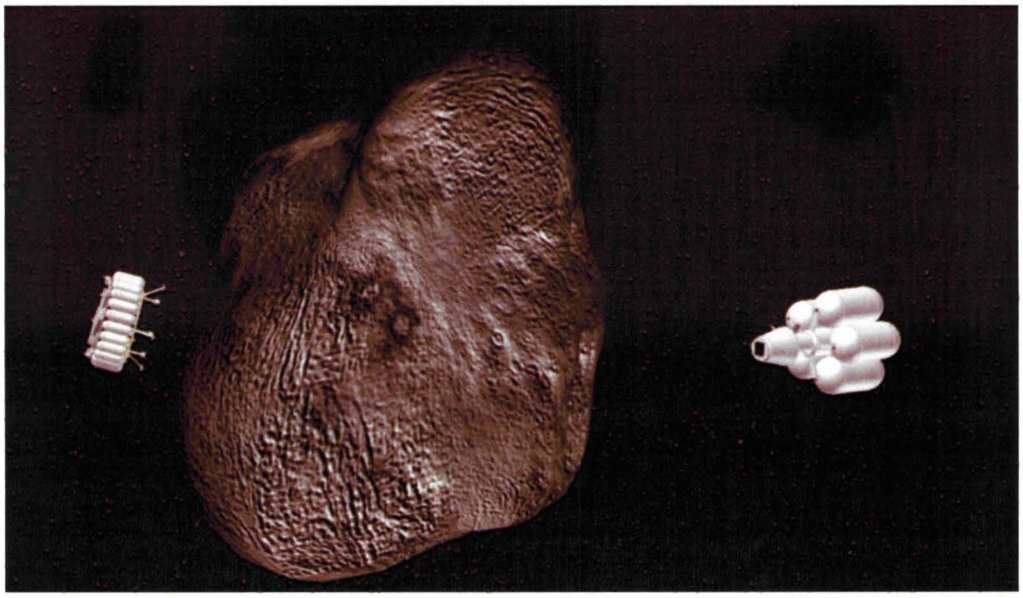

Figure 3: Spacecraft at 1991 JW. This image shows a picture of the lander and the orbiting module. Upon asteroid arrival, the lander will separate and attach itself to the asteroid.

2 5 2 Budget Forecasting

While there is no specified budget for the HAES, it is important to keep track of the expenses of each subsystem to make sure the final design is economically feasible Team COLBERT elected to make the HAES reusable and therefore the cost will be broken down into initial cost for the first mission and the cost for every subsequent mission Table 7 in the appendix displays the complete price breakdown for the Athena mission The total price for the mission was calculated to be approximately $1 35 billion dollars, which is comparable to the $1 3 billion required for each shuttle mission (12) The cost of subsequent missions, however, is nearly half of the initial amount at $700 million due to the need for fewer launches and manufacturing production It is important to note that Table 7 displays prices as of 2010 and therefore the total mission cost is subject to change because the Athena mission will not commence until 2027

2 5 3 Risk Management

Team COLBERT employed continuous risk management through the design process as defined by NASA Continuous risk management involves identifying the risk, analyzing it, planning action to minimize its potential damage, tracking its performance and finally executing various types of control actions to ensure the risk is contained (13) One example of the risk management process was our evaluation of critical technologies

The use of risk matrices was implemented to provide a method of facilitating risk management and providing a semi-quantitative method of analyzing risk to the design As will be discussed in the subsequent section, critical technology on the mission is the venture that provides the most risk to the project schedule and budget

The most significant critical technology being implemented is the VASIMR engine A smaller version of this technology is currently being tested by Ad Astra and results have been promising so far (14) Based on the risk matrix on page 145 of the NASA Systems Engineering Handbook, we assigned the VASIMR a 2 for the likelihood of failure because it is being tested but problems can still occur and 3 5 for the consequences of failure We assigned a 3 5 because if testing on the VASIMR system fails, the spacecraft configuration and launch vehicle selection will have to change due to the large volume of fuel that will need to be carried to complete the mission with a conventional chemical propulsion system Based on the risk matrix table, these two grades correspond to a moderate risk product (13) This means that its development should be followed closely because it can disrupt the schedule Our plan to minimize this risk is to allow seven years of leeway for development In keeping with NASA continuous risk plan, this technology should be tracked to ensure it is keeping with schedule, budget and performance expectations If it fails to stay on track, a control plan will need to be developed to either switch to another type of technology or to put VASIMR back on track This type of risk analysis was conducted on all pieces of critical technology being implemented in Team COLBERT's design It provides a semi-quantitative method for communicating risk status and how to handle this risk (13)

2 5 4 Interface Management

The interfaces between various systems were defined in a previous section Outlining all of these interfaces was the first procedure conducted once system requirements had been identified Because of the small design team and the need to only develop a preliminary design by the RFP, no Interface Requirement Document was developed as suggested by the NASA Systems Engineering Handbook (13)

The interfaces between all different systems were managed in two different ways The first is through having two other system leaders checking to ensure each system meets all necessary requirements for the mission This kept all essential personnel involved in all major design decisions A second method used to manage the interfaces between all systems was having semiweekly meetings where each system lead would present major issues encountered since the previous meeting This procedure allows for the same outputs as NASA in that we are able to control all interfaces and approve interface requirement changes but this design is more efficient for a team of six members

2 5 5 Requirement Traceability

All requirements were made traceable by having the aforementioned semiweekly meetings These meetings allowed the system leaders to check in on the progress of other systems to ensure that they meet all necessary mission requirements and do not conflict with any others For example, when VASIMR was selected as the orbital propulsion engine, the PT&E division was immediately able to voice their concern over the incapability of the current power system to support the engine As a result, it was determined that the most efficient way to provide power to the system would be through a nuclear reactor

In order to ensure all mission requirements have been developed, a checklist was created in the early steps of the design process This list defined all requirements as stated in the Requirements Analysis section and assigned parent and children requirements to each requirement as necessary Priority levels of high, medium and low were also assigned to each requirement so resources could be allocated to each correctly This follows NASA's plan for requirement traceability and validation A sample of the checklists is provided in Table 8 in the appendix but the whole checklist could not be included due to its length

3 Transitioning Critical Technologies

Critical technologies are devices or systems that must be developed in order to serve their function in the system They may incur high development costs and if not developed properly can put the system over budget and behind schedule This section will explain the team's criteria for use of the technologies as well as some methods to reduce their possible risk

3 1 Activities

Activities that may require the use of critical technologies include systems in which either technology has not yet been developed or has not been developed to the level that the Athena mission will require These include the VASIMR propulsion system, the Vapor Core Reactor in the propulsion system, several of the human systems, and the technology used to drill asteroid core samples and hold the spacecraft and astronauts to the micro-gravity asteroid surface The subsequent sections will identify the criteria for using critical technology and develop a risk mitigation plan

3 2 Criteria for Use

Several instances of critical technologies are implemented in the current design The reasons for this are two-fold First, this is a bold mission that will require humankind to push the limits of technology in order for it to be successful The second reason is that per the AIAA RFP, the mission can only be executed between 2018 and 2030 The design team's orbital analyst has determined that a mission to 1991 JW is optimal in 2027 This allows for 17 years of further technological development, making it unreasonable to only use technology available today for the mission

There are three criteria the design team used to decide whether critical technology should be used The first is whether today's technology is capable of completing the desired objective efficiently The second criterion used is whether the technology is on track to be completed at least seven years prior to mission launch The final criterion is assessing if conventional technology can provide adequate safety to the crew If not a critical technology must then be pursued

3 3 Risk

In order to minimize the risk of using critical technology, it must be guaranteed that the technology is projected to be ready seven years before it would be needed for the mission at hand This will increase the probability of the technology being ready in the event of setbacks or delays throughout its development All critical technology risk will be analyzed as stated in the previous risk management section (2 5 3)

4 Integration of Systems Engineering Effort

4 1 Use of Concurrent Engineering

In order for Team COLBERT to meet required deadlines and develop a spacecraft and mission design that meets all RFP requirements, concurrent engineering between standard technical engineering and systems engineering must be implemented Concurrent engineering will allow the team to identify both technical risks to the mission as well as budget and schedule risks, which are the primary concern of systems engineering

Concurrent engineering will also allow technical decisions to be made in a manner that takes into account all systems using the interfaces If systems engineering is not implemented, individual systems will develop without considering other system's needs This could create confusion and impossible requirements for some systems Systems engineering also allows the team to implement certain tools such as trade studies and risk matrices These provide a quantitative or semi-quantitative approach to making design decisions, which will allow the team to have technical support behind all decisions made

4 2 Organization of Design Disciplines

All students on the design team are Aerospace Engineering students at Virginia Tech Despite all students having the similar academic backgrounds, there were many different interests between the students making it easier to divide the project into various divisions The functional divisions used are Communication, Command, and Data Handling (CC&DH), Attitude, Trajectory, and Orbit (ATO), Structures, Power System, Thermal System, Environment System, Propulsion, Human Systems, Scientific Analysis and Attitude Determination and Control System (ADCS)

4 3 Expectation and Frequency of Reviews

In order to meet the project deadlines, the team had meetings with faculty advisor, Dr Kevin Shinpaugh, once a week Apart from these meetings, Dr Shinpaugh also required that our team participate in four major design reviews The first review took place in Fall 2009, the second in February 2010, the third in March 2010 and the final design review will take place in May 2010 These reviews were in the form of a presentation given to Dr Shinpaugh and the remainder of the spacecraft design class For each review, the team was expected to have completed a major portion of the system design

For the first review, the team's presentation consisted of the problem definition, value system design, the analytical hierarchy procedure, system synthesis, and system analysis The team presented the trade studies performed on multiple target asteroid candidates, asteroid anchoring techniques, radiation protection methods, thermal systems, and power systems By this time, the team had not selected the target asteroid but in January 2010, the team concurred that 1991 JW was the most valuable target due in part to its potentially hazardous classification

For the second major design review, the team presented the asteroid candidate along with the ΔV calculations required for the mission The team also presented the spacecraft structure and the launch vehicle that would be required for the mission The power system was further discussed and lastly, the science instruments for asteroid analysis, human systems, and attitude determination and control systems were presented For the third major design review, the team presented the mission architecture and further discussed the propulsion techniques It was decided that VASIMR would be used as the orbital propulsion system for the mission due to power and fuel considerations The team also presented the mining technique that will be used to extract 100 kg sample of asteroid material

For the final presentation that will take place in May 2010, the team is expected to present the complete preliminary design for the HAES This will include the power and thermal systems, human systems, CC&DH systems, mission architecture, and asteroid analysis details

5 Implementation Tasks

5 1 Team Schedule

Figure 7 shows the schedule that the design team has followed since the RFP was released The first stage of the design was to select a target asteroid as well as the type of spacecraft configuration that should be employed After finalizing these two decisions, research into several different systems, including the propulsion system, commenced When these design decisions were made in February 2010, the team began researching human spaceflight systems as well as launch vehicles The design team has written this ESMD Systems Engineering Report and is currently working on the AIAA report, which responds to the given RFP

5 2 System Implementation Schedule

Figure 8 in the appendix shows the planned schedule for system implementation The development of the critical design will begin immediately following the conclusion of the preliminary design stage in early 2010 and will last approximately ten years This design will consist of developing all systems and subsystems to the point where they are ready for testing and production After all of the required systems are complete, the testing phase will take place between 2020 and 2024 Upon completion of the testing phase, the designs will be sent into production with a completed system ready before September 2027 The Athena mission will commence on September 21, 2027 with a launch into LEO where the lander, crew capsule and VASIMR systems will be assembled and tested The remainder of the mission will consist of a 75-day transfer both to and from the asteroid with ten days spent at 1991 JW performing the required drilling and scientific analysis

Appendix

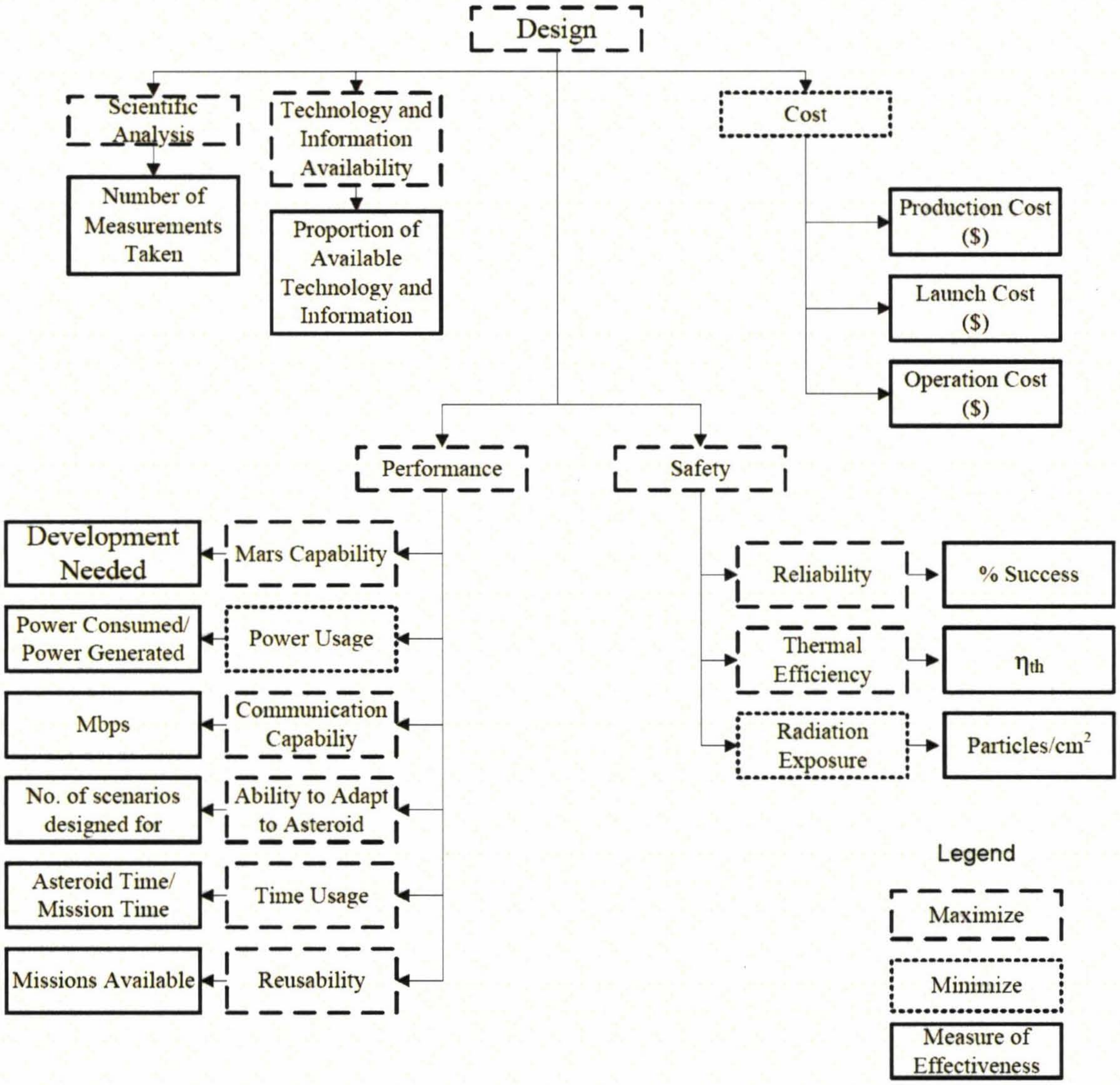

Figure 4: Objective Hierarchy Chart. This chart shows which objectives need to be minimized and maximized and what criteria will be used to judge mission success. Each value will undergo an analytical hierarchy process to judge relative importance.

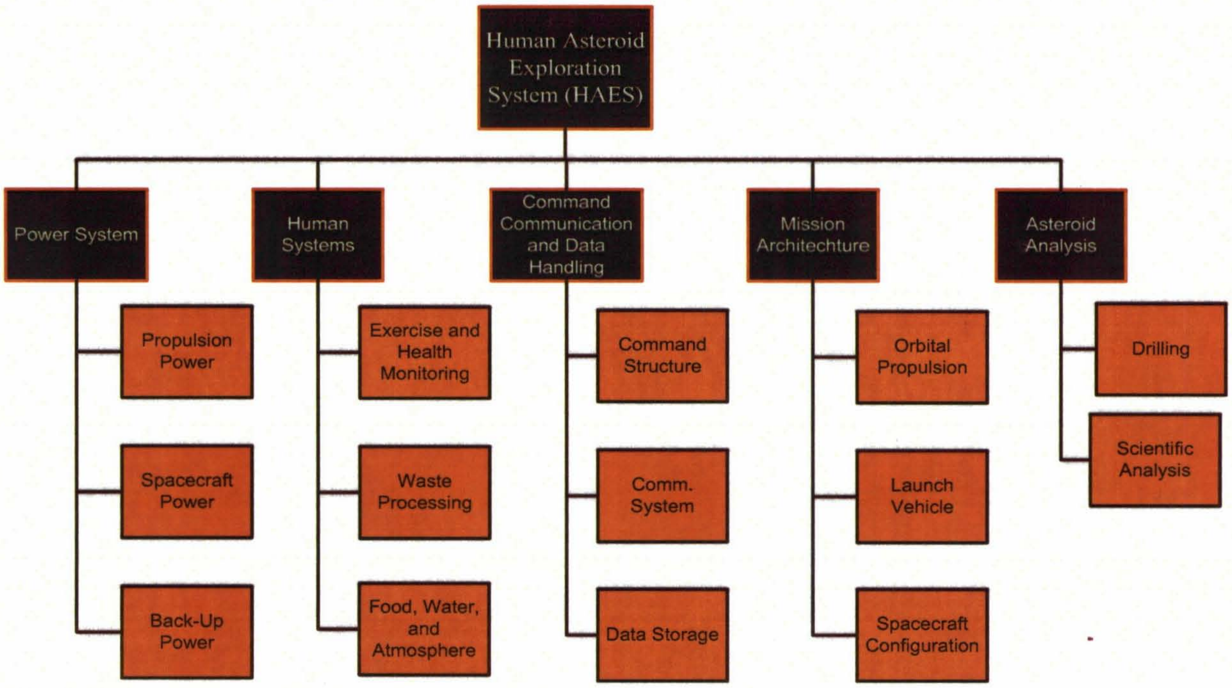

Figure 5: Functional Allocation. This diagram shows a reduced system breakdown of the systems from their upper levels to their subsystems.

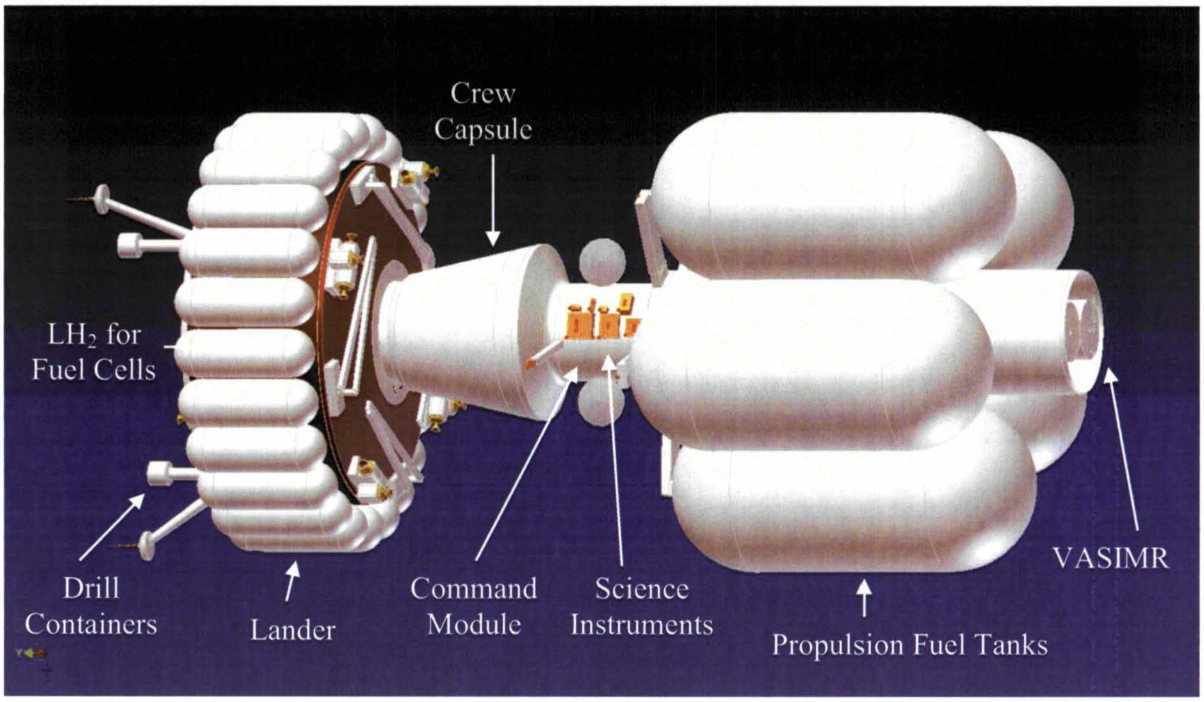

Figure 6: Full Assembly in Space Transport Configuration. This angle shows all of the scientific instruments and the VASIMR engines located at the aft end of the spacecraft.

Table 7: Budget for Initial Cost and Each Subsequent Mission (9; 15; 16; 17). This table displays the budget for the HAES. The initial system cost is $1.35 billion but due to its reusabilty, each subsequent mission is projected to only cost $694 million.

System Component	Component Description	Initial Cost (FY10$)	Additional Missions (FY10$)
Structure		$10,000,000.00	-
ADCS	Dry Wt.	$500,000.00	-
	Pointing Accuracy (deg)	$40,000.00	-
	Pointing Knowledge (deg)	$20,000.00	-
Power	Nuclear Reactor	$90,000,000.00	-
	Solar Panels	$10,000.00	-
	Fuel Cells	$30,000.00	-
	Electrolysis Machine	$5,000.00	-
CC&DH	TT&C + DH wt. (kg) 30 kg	$11,819.91	-
	Data Storage Capacity (512 MB)	$8,439.24	-
	Downlink Data Rate	$6,023.68	-
Human Systems	VFHU, STEVE, health monitors	$9,200,000.00	-
	Treadmill (COLBERT)	$5,000,000.00	-
	Spacesuits	$50,000,000.00	$50,000,000.00
Science	Instruments	$299,507.00	-
	USDC × 18	$646,200.00	-
Launch Vehicle	Falcon 9 × 7	$360,500,000.00	$309,000,000.00
	Jupiter 130	$160,000,000.00	-
VASIMR	Engine × 2	$160,000,000.00	-
Capsule		$60,000,000.00	$30,000,000.00
Refurbishment		$0.00	$100,000,000.00
Subtotal		$906,276,989.84	$489,000,000.00
Integration and Test		$125,972,501.59	$50,000,000.00
Program Level		$207,537,430.67	$100,000,000.00
Ground Support Equipment		$59,814,281.33	-
Launch & Orbital Ops Support		$55,282,896.38	$55,282,896.38
Total		$1,354,884,099.81	$694,282,896.38

Table 8: Sample Requiremnt Checklists. These tables exist for all functional divisions and were used to ensure all mission requirements were completed.

ID	Requirement	Rationale	Parents	Children	Priority
MR-01	At least 100 kg of asteroidal material must be extracted	Mission Requirement	-	SA-01	High
MR-02	Mission must travel to NEO	Mission Requirement	-	AA-01	High
MR-03	At least 2 astronauts must be carried	Mission Requirement	-	HS-01, SC-01,LV-01	High
MR-04	500 kg of cargo must carried to surface of Asteroid	Mission Requirement	-	SC-02	High
MR-05	Astronauts must be capable of performing EVA's	Mission Requirement	-	HS-02, SC-03	High

ID	Requirement	Rationale	Parents	Children	Priority
SC-01	System must be carrying of securing two astronauts	Mission Requirement	MR-03	LV-21	Medium
SC-02	Structure must be able of carrying 500 kg	Mission Requirement	MR-04	LV-07	Medium

ID	Requirement	Rationale	Parents	Children	Priority
HS-01	Develop system to maintain health of at least 2 astronauts	Must maintain health	MR-03	SC-15, PS-02	Medium
HS-02	Design or find spacesuits capable of EVA in high radiation environment	Mission Requirement	MR-05	SC-11, PS-22	Medium

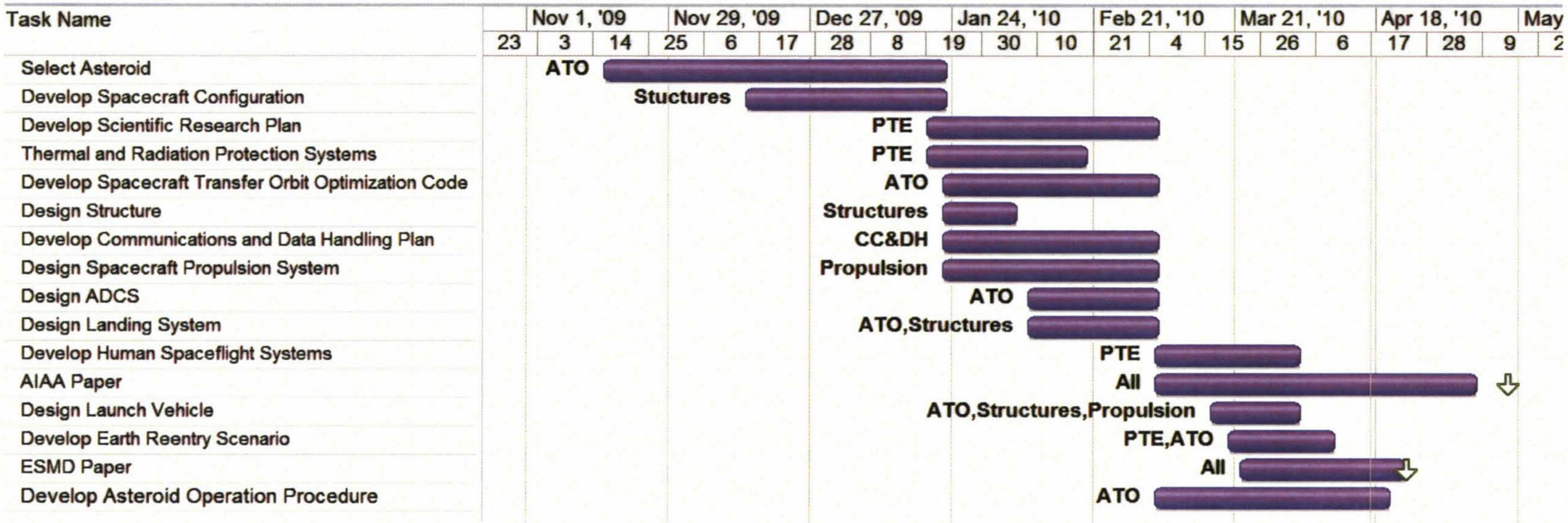

Figure 7: Gantt Chart displaying Team COLBERT schedule. The design team followed this schedule this semester to ensure that all mission requirements were completed in the necessary timeframe.

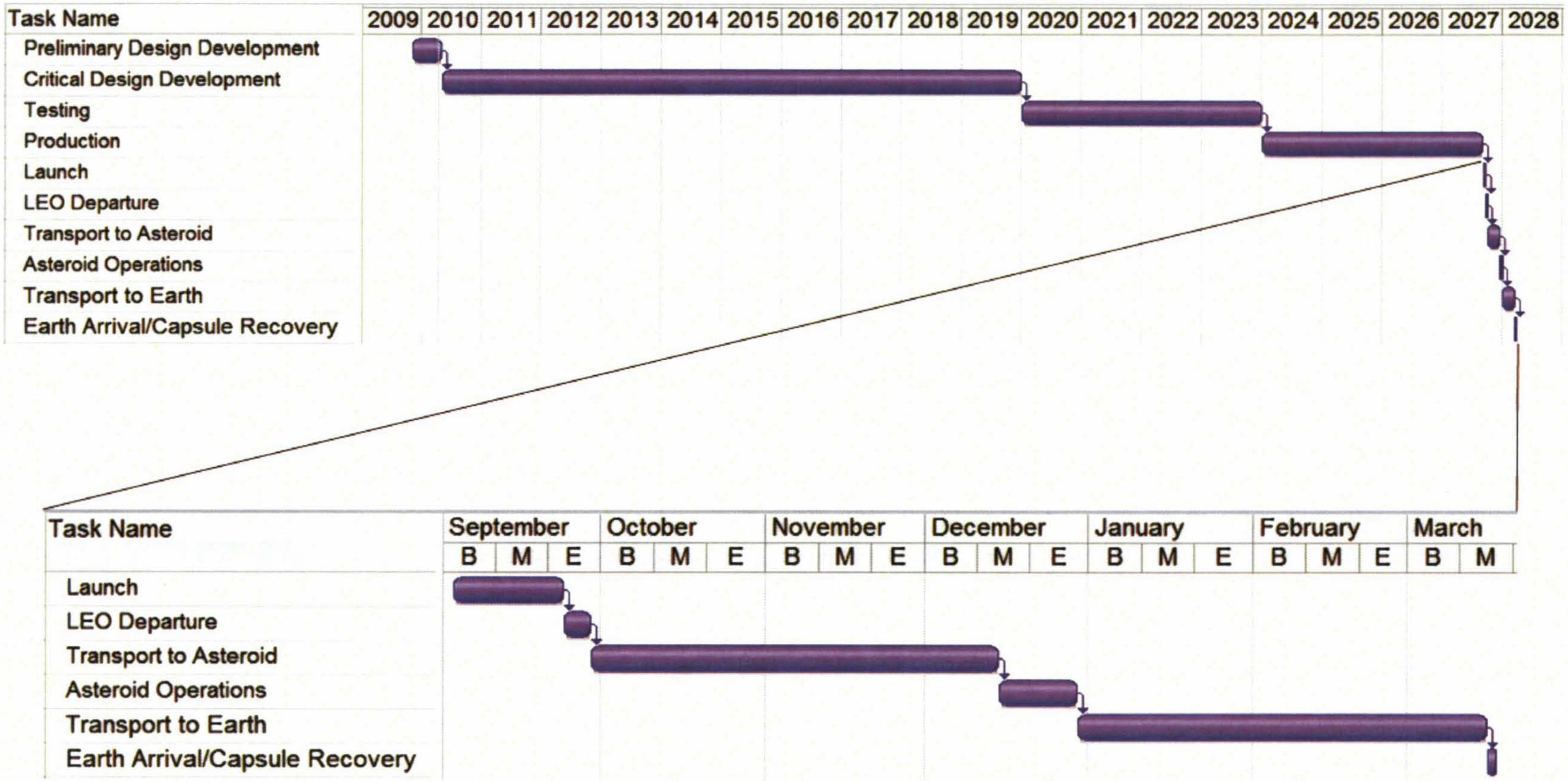

Figure 8: Gantt Chart displaying Mission Timeline. The upper chart shows the overall mission schedule. When the preliminary design is finalized next month, the critical design stage will begin and last for ten years. It will then be followed by testing and production phases before the mission commences. The lower chart shows the Gantt chart zooms in on the mission timeline. The mission will last 180 days from the time the astronauts board the launch vehicle to the time that they are recovered.

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