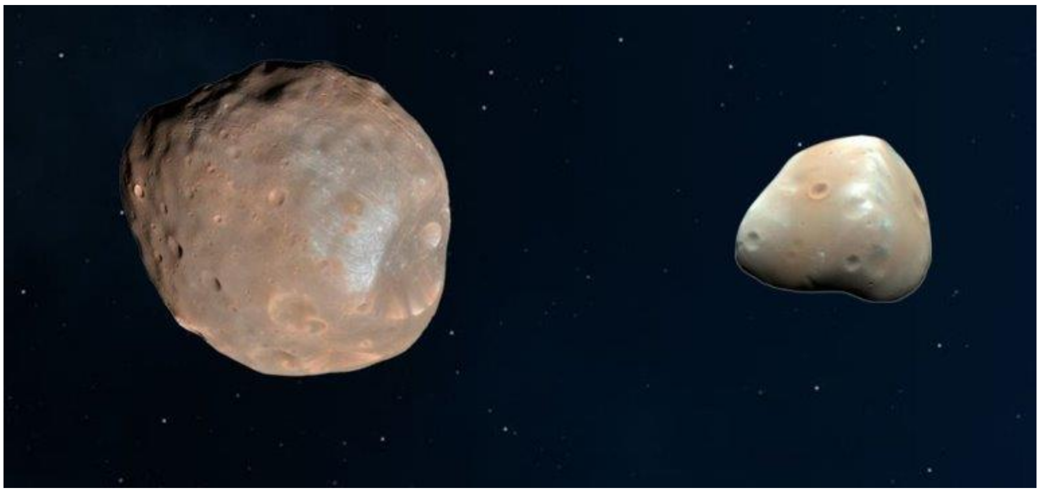
AIAA Foundation Undergraduate Space Mission Design Competition

SCOTT: A Martian Moon Exploration Excursion Vehicle FDR



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List of Abbreviations

DST: Deep Space Transport

EEV: Exploration Excursion Vehicle

A: Area

M: Moment

Isp: Specific Impulse

I: Moment of Inertia

P: Load

WT: Total Weight

Psi: pounds per square inch

m/s: meters per second

in: inches

m: meters

y: moment arm

e: eccentricity

r: radius

1 Executive Summary

In recent years, the development of space exploration and technologies has been brought to attention with a focus on the planet Mars. With this, many companies have set out to develop space vehicles for space and surface excursions of Mars and Mars's moons, Phobos and Deimos. With Mars being a location for human civilization to inhabit, a look into the best solutions for travel to Mars has been developed. The solution of focus that has been developed and presented by NASA (National Aeronautics and Space Administration) is to imply an incremental exploration approach. In this solution, a focus is brought to developing bases on Mars's moons Phobos and Deimos. To first begin this process of building bases on the moons of Mars, frequent missions to the surfaces of both moons are required. With the goal of building bases on the surfaces of Phobos and Deimos, NASA has set out in search of space technologies to fulfill the task at hand. The technologies in need for NASA's plans are a surface rover, as well as a transporter for the rover.

Presented in this document are developments for the space rover and transporter for the rover. With an already existing model for the surface rover designed by NASA, the surface rover presented in this paper will take similar aspects from this rover as well as presenting innovative technologies the rover shall acquire. As for the transporter, innovative ideas and technologies are presented to solve various issues when embarking on such travels to the surfaces of both moons. A few concerns focused on this paper when considering the surface rover are traction from the rover, living space, payload capabilities, and maneuverability of the rover while on the surface. A few concerns regarding the rover transporter are propulsion systems, docking systems, and safety of the rover while being joined in transportation.

The value of the solutions presented in this document range from simple solutions for safety hazards, to solutions for the complete exploration by humans of Mars and the moons of Mars. When considering the expansion of human civilization, each step in progressing the technologies to make humans multiplanetary is of the utmost importance. Presented in this document are solutions focused on the excursions of both Phobos and Deimos but are not limited to the singular goals given by NASA.

2 Introduction

2.1 Introduction

Human civilization is threatened by global warming, and the search for habitable expansions outside of the planet is higher than ever before. To achieve that habitable expansion, it is critical to discover the moons of Mars. Mars is the closest habitable planet for human civilization and its moons are critical to study to see if there are any significant discoveries. To include Mars's moons in the expansion of human life to Mars is prominent in the discovery of new developments for possible missions. Along this journey there are a few goals to be reached. The first of these goals is to establish key developments on the surfaces of both moons. Here astronauts will build and test tools and systems that would be necessary for deep space transportation. The second goal is to determine the best plan to land large scale systems on the surface of the moons as well as Mars. From this goal the key development is to be able to test descent systems prior to missions to the surface to Mars. The last goal of sustaining incremental trips to the surfaces of both moons and Mars is a rover that will sustain life on both moons and the Mars surface.

2.2 Overview

NASA & AIAA have collaborated and given a project proposal for college students to develop a design prototype for a Martian Moon Excursion Vehicle that can habitually carry 2 passengers to the surface of Mars's moons and the mission profile to last no more than 30 days. The way the team will execute the proposal will be to develop a design prototype for the excursion vehicle that is inspired by NASA's current EEV model they have developed whilst also developing a design prototype of the transporter vehicle that will drop off the excursion vehicle on both moons. While some aspects of the NASA design prototype will resemble the prototype presented in this paper, a few differences will be brought to the components of gravity control systems, propulsion systems, and traction control of the wheels. The name of the duo-system consisting of the EEV & transporter presented will be named "SCOTT" (acronym for search, command, occupy, transport, transform) inspired by the tribute the team put towards Kid Cudi (real name Scott Mescudi), an artist who made space exploration-related albums. The team's name "Embrace The Martian" also pays tribute to that being one of Kid Cudi's song titles directly bringing relevance to this project.

2.3 Objective

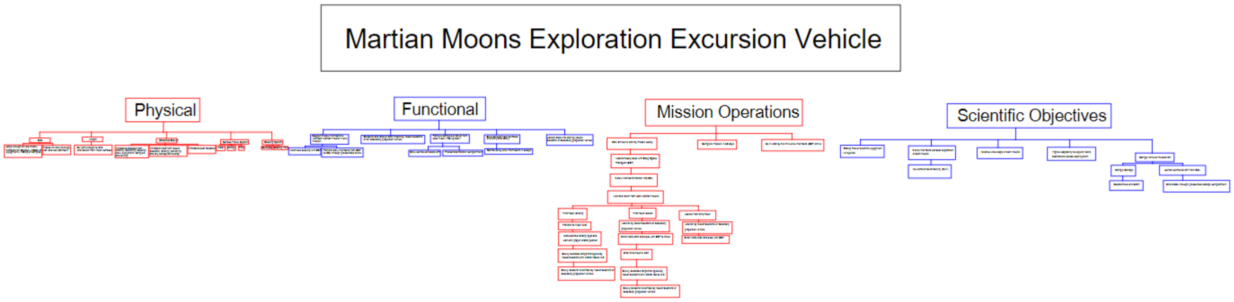


Figure 1. Overall SCOTT Flow Chart

The SCOTT flow chart contains four overall objectives that need to be accomplished, which are physical, functional, mission operations, and scientific objectives as shown in figure 5.

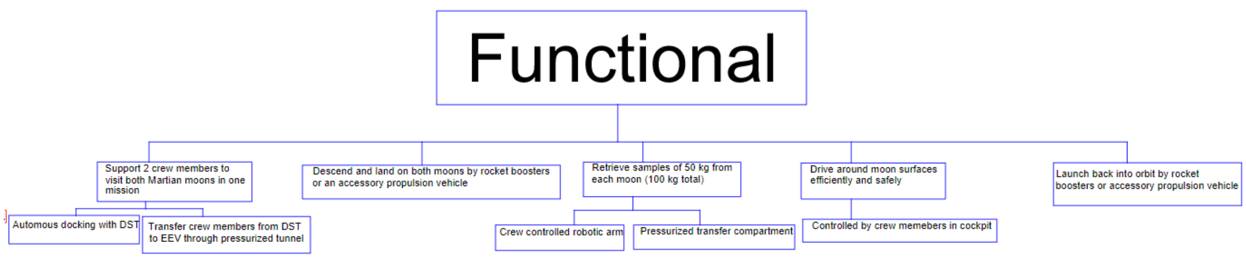


Figure 2. Functional Flow Chart

For the functional objectives, the SCOTT must be able to support two crew members to visit both Martian moons in one mission. To accomplish this, the SCOTT shall dock automatously with the DST and be able to transfer crew members from DST to EEV through the pressurized tunnel. The SCOTT shall descend and land on both moons by the transporter’s rocket boosters. The SCOTT shall retrieve samples of 50 kg from each moon, with a total of 100 kg each. Possible ways to achieve this are to implement a crew-controlled robotic arm and a pressurized transfer compartment. The SCOTT shall be able to drive around the moon surfaces efficiently and safely by being controlled by the crew members in the cockpit. The SCOTT shall launch back into orbit by the transporter.

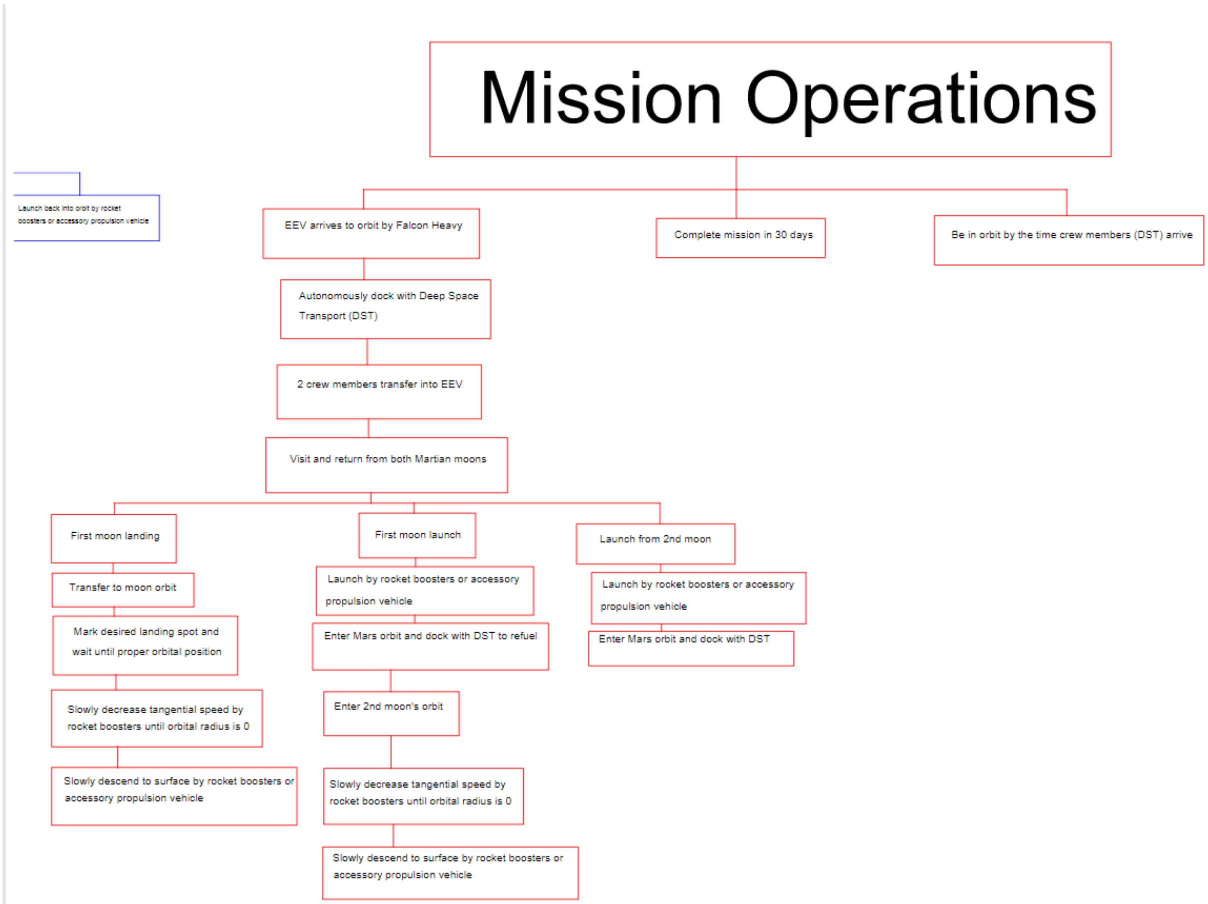


Figure 3. Mission Operations Flow Chart

SCOTT has three mission operation objectives. Two crew members will transfer onto SCOTT from the DST to visit and return from both Martian moons. The first moon landing will be accomplished by transferring to moon orbit, marking the desired landing spot, slowly decreasing the tangential speed by using rocket boosters until orbital radius is zero, and slowly descend to the surface via the transporter's boosters. After that, the SCOTT shall launch from the first moon and enter the second moon's orbit, then descend on the moon in the same fashion as the previous. Finally, the SCOTT shall launch back into orbit and dock with the DST. This mission cycle is to last a maximum of 30 days. The SCOTT shall be in orbit by the time the crew members arrive, as stated in figure 7.

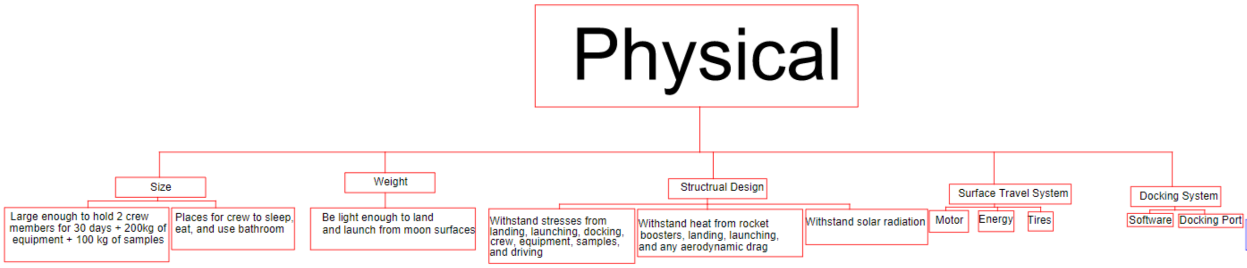


Figure 4. Physical Flow Chart

The SCOTT has five physical objectives. For size considerations, it must be large enough to hold two crews for thirty days and be able to hold 200 kg of equipment and 100 kg of samples. There should be places for the crew to sleep, eat, and use the bathroom. For weight considerations, it should be light enough to land and launch from moon surfaces. For structural design, it should be able to withstand stresses from landing, launching, docking. It should also be able to withstand heat from rocket booster, landing, and launching. It should also withstand solar radiation. The rover will comprise of motor, its energy source, and tires. The docking system will include software and docking ports.

2.4 Justification (Why?)

This project is a small stepping stone to determine whether life can exist in our solar system outside of Earth. It would also push science and technology forward as progress is made towards this goal. Future generations can research to explore other galaxies. It can also make advancements in lunar sample collection excursions.

2.5 Project Background

To achieve the goal of landing humans on the surface of Mars and returning them safely back to Earth, an incremental exploration approach provides the safest and most sustainable results. Therefore, NASA and international partners are planning the next steps of human exploration by first establishing assets near the Moon and Lunar surface where astronauts will build and test the systems that are needed for deep space exploration with eventual human missions to the surface of Mars.

2.6 Problem Statement

Without the landers to bring the surface assets and the crew to the surface of Mars, the incremental exploration strategy stalls with the crew reaching Martian orbit. Previous architecture analysis proposed the possibility of crew exploration of the Martian moons to provide more time for the descent system to be developed and tested. Unfortunately, these endeavors typically involve the development of additional hardware that does not directly contribute to the efforts of surface missions and potentially draws resources away from the primary mission. Thus, these missions are typically not considered within a Mars surface mission integrated exploration strategy.

2.7 Design Requirements and Constraints

The SCOTT, a Martian moon exploration excursion vehicle, shall be able to support two crew members. SCOTT shall not cost more than $1 Billion USD, which includes the cost to launch. The SCOTT shall be able to make a trip to Deimos and Phobos, the moons of Mars. The SCOTT shall be able to complete the expedition in no more than 30 days. The SCOTT shall be able to sustain the crew members without having to leave the vehicle. The SCOTT shall be able to hold up to 200 kg of scientific experimental equipment, which must be able to fit through the pressure tunnel in the DST. The SCOTT shall be able to hold 50 kg of Martian material minimum from each moon. The SCOTT shall autonomously dock with the DST. The SCOTT shall be able to quarantine the samples from the crew until arrival on Earth. The SCOTT shall be able to have a propulsion system that's sufficient to propel the vehicle from orbit to the surface of the moons. The SCOTT shall not be egregiously large for the mission of its caliber.

2.8 Weight Analysis

A weight analysis is performed for this mission to determine the necessary design requirements to carry out all the objectives. The main goal of the weight analysis is to obtain the thrust requirements for the spacecraft. Once the thrust requirements are determined, the propulsion system can then be designed. The weight analysis serves as one of the first steps in the design of the spacecraft itself.

Table 1. Weight Analysis

	A	B	C	D
3				
4			**Weight Analysis**	
5		**Item**	**Weight (lbs)**	**Source**
6		Space Exploration Vehicle	6600	NASA
7		Sample Retrieval Mechanism	100	Design Assumption
8		MSL Skycrane+Fuel	10555	space.skyrocket
9		2 Crew members	400	CDC
10		Clothing	6	International Journal of Obesity
11		Moon Samples	230	Project Guidelines
12		Scientific Equipment	330	Project Guidelines
13		Food	330	NASA
14		Water	90	NASA
15		Fuel	9417	Superdraco Fuel Data
16	Included in B8	OMS Engines	260	NASA
17	Included in B8	Viking 1 Lander	1261	National Space Science Center
18	**Total Weight**		17155	
19	**Payload Weight**		7738	
20	**Payload /Takeoff Ratio**		0.45	

The weights in the above figure are gathered from previous missions, project calculations, or project requirements. The NASA Space Exploration Vehicle is the model for which the EEV of this mission is based on. The Mars Science Laboratory Sky Crane is the model for the transporter of the mission. It is important to note that fuel is included with the sky crane weight. Those are the two main systems which will be designed and modified. They are also responsible for over 45% of the weight if fuel is not included. Based on the general weights of all the components needed, the starting weight requirement of all systems in this mission is 17,155 lbs. The payload to takeoff ratio is 0.45. This seems incredibly high for a spacecraft; however, the scope of the mission starts in Mars' orbit; therefore, the weight required to takeoff from Earth is not included in the calculation. If it was included, the payload to takeoff ratio would be less than 1%.

Given the necessary burn time and velocity changes for the orbital maneuvers in Table 1, a thrust requirement of 29,622 N is to be designed for.

2.9 SCOTT Mission Profile

The SCOTT begins its expedition in a 5-sol orbit of Mars in the year 2040. It will then be met by the deep space transport (DST) and docked while in the 5-sol orbit. Two crew members will transfer into the SCOTT and the vehicle will separate from the DST. The two-part vehicle, the EEV and propulsive transporter, will make a series of burns to travel from the original parking orbit to the orbit of Deimos where the SCOTT will land. The SCOTT descends to Deimos by means of a propulsive transporter. The crew will stay on Deimos for roughly 5 days, performing experiments and collecting samples. After the mission on the first moon is completed, the SCOTT will launch into the orbit of the first moon. Soon after, the vehicle will transfer to the orbit of the second moon: Phobos. Upon descension on the second moon, the second leg of the expedition begins for sample collection. After a successful expedition, the SCOTT will launch into Phobos' orbit and transfer back to the original 5-sol parking orbit. The SCOTT will end the journey by docking autonomously with the DST so the crew and samples can be transferred.

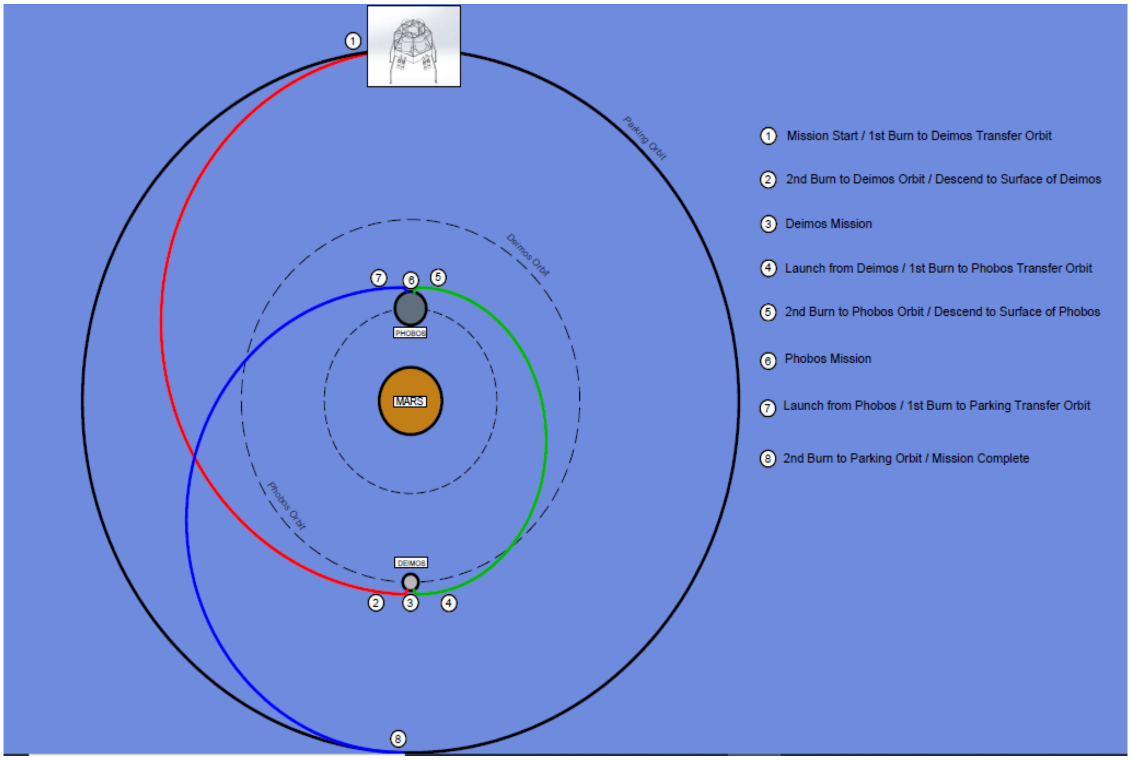


Figure 5. Mission Profile Diagram

Figure 6. Option for the SCOTT Mission Profile for a single rover. Figure 6 shows the list of steps in the mission using General Mission Analysis Tool (GMAT).

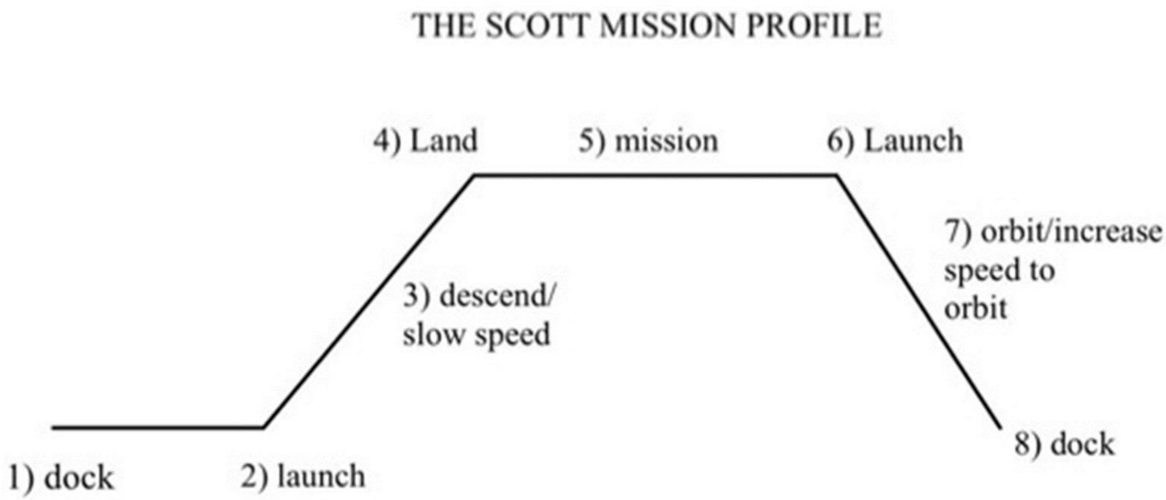


Figure 7. Option for the SCOTT Mission Profile for two rovers

As shown in figure 7, this is a simplified mission profile for SCOTT which shows the basic mission steps in a linear diagram.

Table 2. Change of Weight for Each Mission Step

Mission Profile Data			
Step	**Time (days)**	**Beginning Weight**	**End Weight**
Parking Orbit to Deimos	1.49	17155	14424
Deimos Mission	9	14424	14424
Deimos to Phobos	0.24	14424	11535
Phobos Mission	2	11535	11535
Phobos to Parking Orbit	0.93	11535	7738

The above weights are determined from the orbital mechanic requirements discussed later in Sections 7 and 8. The orbital mechanic analysis determines the thrust requirements of each step of the mission. Given the specific impulse of the engine, the mass flow rate of the fuel can be determined.

Equation 1. Specific Impulse

$$I_{sp} = \frac{1}{g_0}\frac{F_{thrust}}{\dot{m}_{propellant}}$$

From this weight analysis, it is determined the initial weight of the spacecraft is 17,155 lbs at the start of the mission. The spacecraft will weigh 7738 lbs when it returns to the initial orbit at the DST.

2.10 System Components

The SCOTT has a variety of system components that intermingle with each other to ensure smooth operation. These components will be researched and studied thoroughly and are listed as follows: Avionics, Electrical Power, Thermal Systems, Propulsion, Instruments, Mechanisms, Command/Data handling systems, Antennas, Telecom, and Guidance/Navigation. The relationship between each part can be shown using the following system block diagram.

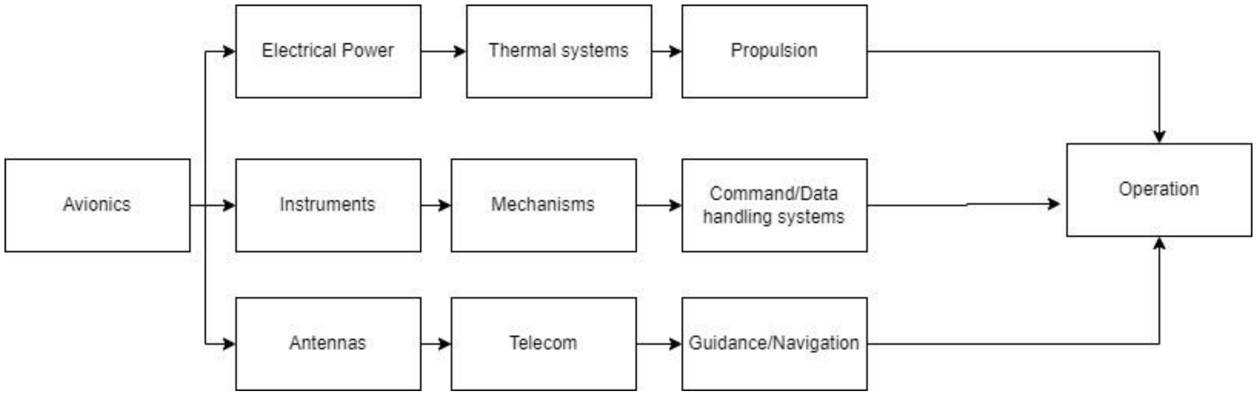


Figure 8. SCOTT System Block Diagram

2.11 Rocket-Powered Sky Crane Transporter

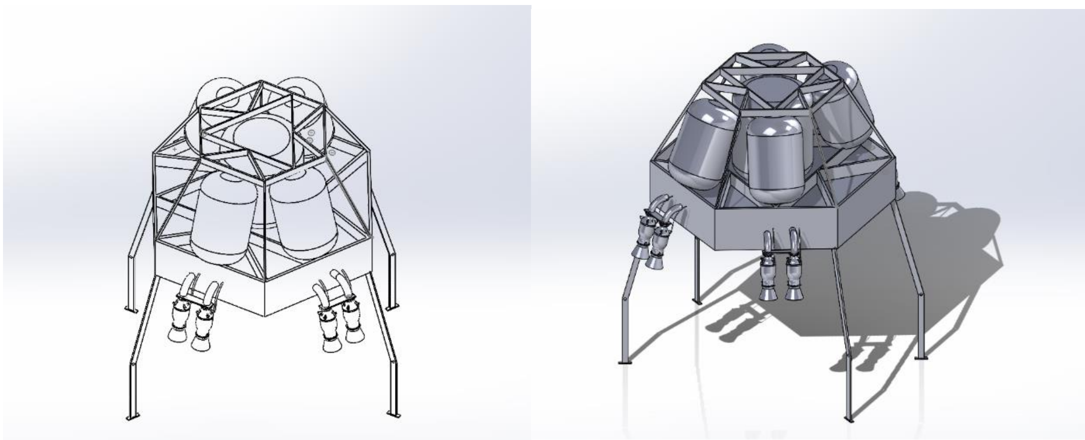


Figure 9. Rocket Powered Sky Crane CAD Model

The propulsive transporter that delivers the EEV from the DST to each orbit and to the surface of each moon is based on the Mars Science Laboratory (MSL) Sky Crane that was used to successfully deliver the Mars Curiosity Rover to the surface of Mars in 2012. The MSL Sky Crane was equipped with eight engines symmetrically placed around a hexagon structural frame. Each engine could produce a thrust of 3060 N for a maximum total system thrust of 24,480 N.

The sky crane transporter for this current mission will be similar to the MSL Sky Crane, except that it will have additional responsibilities and, therefore, a modified design. The MSL Sky Crane's only purpose was to deliver the Rover from atmospheric entry to the surface of Mars. The transporter in the Phobos and Deimos mission will deliver the EEV to each surface as well as making all the orbital maneuvers from the DST to each moon. Because of this added requirement, the transporter in this project will use different, more powerful engines and more fuel.

A propulsive landing was chosen for this mission because the atmosphere of both Phobos and Deimos is negligible, making a parachute landing impossible.

Figure 10. MSL Sky Crane Concept from NASA [14]

The above figure is a NASA depiction of the MSL Sky Crane delivering the Mars Curiosity Rover to the surface of Mars. A similar concept is applied to the Mars' moons mission. The EEV will be attached to the transporter from the DST until it makes a slow descent landing on the surface of the first moon. At this point, the transporter will de-attach and will land on the surface of the moon until takeoff is needed. The transporter will be controlled by crew members in the DST.

The transporter will be equipped with eight SuperDraco engines. These engines were designed by SpaceX to be used as a launch abort system and powered landings. This system of SuperDraco engines provides a maximum thrust of 534,000 N. They will not run at full thrust at any point in the mission, however. This maximum thrust is 18 times greater than the required thrust given in section 2.8 [14].

2.12 Gravitational Stability Technology

A major problem of this mission is the microgravity conditions on both Phobos and Deimos. The EEV and crew will have enough mass not to float off the surface of the moon back into a Mars' orbit; however, if the dry weight is the only force keeping the vehicle down, the vehicle will not have much traction and may spend too much time waiting to descend back to the surface after going over a bump or slope. This could make for an inefficient mission.

To combat this problem, four reaction control system (RCS) thrusters will be placed on the sides of the EEV. Each thruster has a nozzle in four directions and can move the vehicle in any direction. These thrusters will fire upwards when there is not enough weight keeping the EEV on the surface, thus producing thrust downwards and maintaining traction with the EEV tires and the moon surface.

3 Trade Research

The SCOTT involves a plethora of areas to research into to ensure a successful vehicle that satisfies all the constraints and requirements. Within the research disciplines such as astrodynamics, propulsion, avionics, spacecraft design and performance, one area that will researched would be utilizing different propellants and the effect of it on fuel consumption and weight of the vehicle. Another area to consider would be studying the orbital mechanics and the distance between legs of the mission to determine the most optimized path to prevent the waste of fuel and resources. Another area is to investigate are the capabilities of different companies that specialize in solar panels, and their efficiency as well as cost are considered. Another area to perform a trade study in would be to determine the most optimized structure of the vehicle based on past designs as well as consideration of the power it requires to operate. The final area of research would be to determine the interior arrangement of the vehicle to sustain the crew as well as keeping them separated from the Martian material when not undergoing research.

3.1 Engine and Fuel Selection

An important component of any vehicular design is selecting the engine to provide the movement necessary to complete the task at hand. Another paramount component is the type of fuel, as the engine will not be able to function without it. It was decided by the group that the engine will utilize hypergolic propellant. Hypergolic propellants are "storable liquid fuel that found favor in the United States for use in orbital spacecraft engines" [26]. A key advantage that hypergolic propellants have is that they can be controlled with extreme precision with two valves, eliminating any complexity in the starting procedure. This, in turn, results in a predictable thrust that can be modeled by calculations and theory. It was utilized by the "returning LEM on the Apollo moon missions". Hypergolic propellants are also less likely to explode when starting the engine, which is called a hard start if it occurs [28].

For the engine selection, the choices dwindled down to spacecraft engines that could utilize hypergolic propellants. The criteria for engine selection are decided by the required thrust and the specific impulse. Specific impulse, or Isp, is the efficiency of the engine in seconds. It is very similar to thrust specific fuel consumption used in aeronautics. The first engine that was researched is the SpaceX SuperDraco with a thrust of 71 kN and a specific impulse of 300 s [18]. The engine can be shown below.

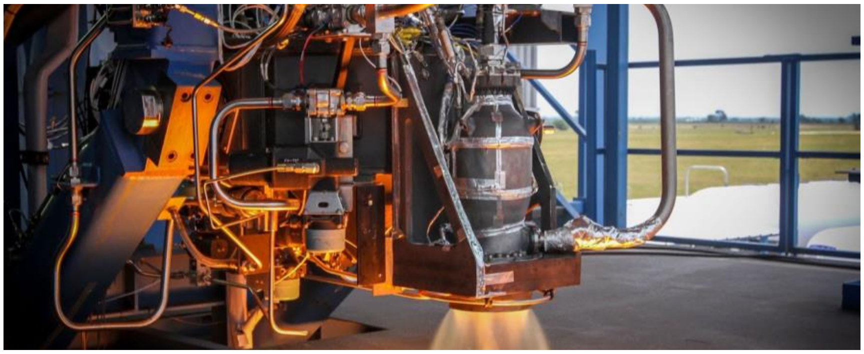


Figure 10. SuperDraco engine

The next engine to be studied is the Aestus II engine, which was developed in 1988-1995 at the Ottobrunn Space Propulsion Centre. This engine has a thrust of 29.6 kN and a specific impulse of 324 s. It is capable being reignited multiple times [29]. The engine is shown below.

Figure 11. Aestus II engine

The final engine is the Vikas 4B, which has a specific impulse of 293 s and a thrust of 78.4 kN. The engine is shown below.

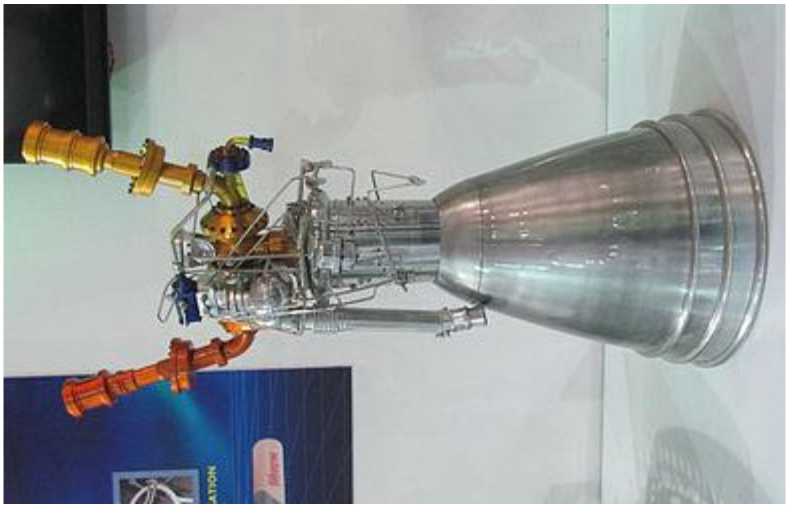


Figure 12. Vikas 4B engine

Upon completion of the trade study on the various engines, the results are shown below.

Table 3. Engine Selection

Engine Type	Specific Impulse (Isp) (s)	Mass (kg)	Length (m)	Diameter (m)	Burn Time (s)	Thrust (kN)	Status
SuperDraco	300	Not provided	Not provided	Not provided	Up to 3 mins	71	Operational
Aestus II	324	138	2.2	1.31	162.97	29.6	Operational
Vikas 4B	293	Not provided	3.7	1.80	193	78.4	Operational

It was difficult to compare the size of the engines since SpaceX does not provide the dimensions. However, upon comparison of the specific impulses and thrust, it was decided that the Aestus II will be the engine of the sky crane component of SCOTT. The Vikas 4B is slightly larger than the Aestus II but has a larger thrust output. The only downside is that it is slightly less efficient than the Aestus II, However, it will be discussed in chapter 7 that the largest thrust is around 29 kN, which matches the output provided by the Aestus II [18] [27] [29]. The SuperDraco is chosen for its high thrust output, efficiency, and due to possibly being the lightest engine.

As a comparison, the original sky crane utilized eight MR-80B thrusters which have a specific impulse of 200 to 225 s and a thrust of 31 to 3603 N. This engine utilizes hydrazine propellants, which are reliable and can be stored at room temperature and reignited multiple times. [30] [31]. The thrusters can be shown below.

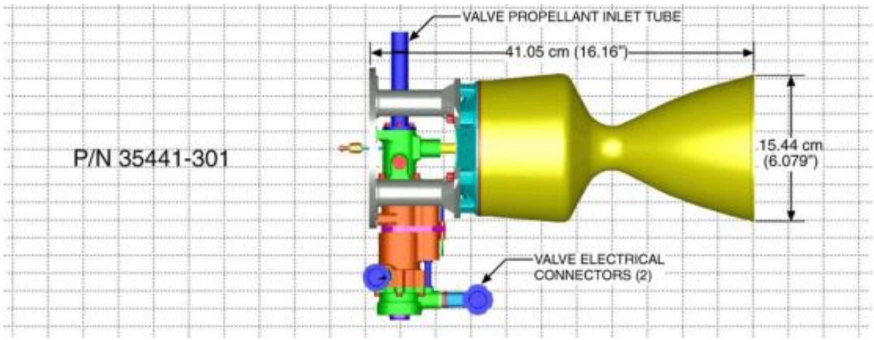


Figure 13. MR-80B thruster

4 Literature Review and Resources

The following items are currently being utilized as a resource for the development of the SCOTT.[1] The information on the moons of Mars will be researched thoroughly through NASA's website.[2] The information on the various propellants that will be used to operate and launch the vehicle will be extensively researched through a referenced project of a previous group at Kennesaw State University, which will be used sparingly to guide the team towards the right direction, which can be found in digital commons.[3]

[4] Means of transportation on Phobos and Deimos are discussed. Since both Martian moons are microgravity environments, a clever design is required in order to efficiently travel on th surface of the moons without losing traction or floating upwards. NASA has come up with vehicles called "Robotic Hedgehogs" which are spherical vehicles with spikes on the outside that stick into the surface and prevent the vehicle from leaving the surface. The issue with this idea is that no crew members can fit inside the hedgehogs. They are unmanned vehicles. The spike idea can still apply to a crew mission if it is utilized correctly.

[5] A Japanese aerospace company, MMX, has planned and designed for a mission to visit both Martian moons and collect samples. The mission is planned for the mid 2020's. Information is provided on the planned trajectories and orbital maneuvers to get to each orbit. The mission calls for an elliptical parking orbit with a plane change before it meets up with Phobos. Three maneuvers occur to travel from parking orbit to Phobos

[6] The optimization of parking orbits is discussed by NASA for roundtrip Mars missions. The minimization of delta V is heavily noted. A smaller delta V during orbital maneuvers equates to less required thrust and/or fuel. It is of great importance to the mission. This paper discusses orbital missions both to Mars and to both moons. An orbital maneuver called the bi-elliptic apotwist, which is a 7-burn sequence, is analyzed to determine an optimum maneuver to reach the desired parking orbit. The paper mentions that trips to Phobos and Deimos are essentially just orbit missions since the gravity of each moon is almost negligible.

[7] The information for further moon-related detailed dimensions will be referenced through the WayBack website.[8] The entirety of the vehicle will be fully inspired by the existing NASA EEV (Exploration Excursion Vehicle) that has been designed in this document in which will be used for calculations & specs of the vehicle. The EEV is an incredibly capable vehicle designed for rocky, tough terrain in low gravity. The main difference between this EEV on the Moon versus the EEV on Phobos and Deimos is the need for thrusters on the latter. They are needed to keep the vehicle down at the surface. The raw weight of the EEV will keep it on the surface of the Moon.

[9] *Fundamentals of Astrodynamics* by White, Bate, and Mueller discusses in-depth about a wide range of topics in the field of astrodynamics. The book discusses two-body orbital mechanics, orbit determination from observations, basic orbital maneuvers, position and velocity as a function of time, and lunar trajectories. In-plane and out-of-plane orbital transfers are analyzed.

This book provides a sufficient amount of orbital information, examples, and equations for the calculations of Martian moon orbital transfers from a specified parking orbit.

[10] [11] [13] These sources give different accounts of the same mission. They describe the Mars mission that this project is based on the Mars Curiosity Rover Landing launched in 2011. [13] The IEEE Aerospace Conference Journal of 2007 published the plan for the MSL descent and landing system before the mission occurred. The thoughts behind each design are described by NASA engineers involved in the project. This is where the idea of using a rocket powered sky crane was obtained from.

[12] A list of Mars landers is given in a table. A list of all 21 attempted Mars landers is given along with information regarding launch date, mass, landing region, success or failure, country of origin, and entry velocity. This provided information on previous missions to the surface of Mars. The weights given were considered in the weight analysis.

[13] This article from the 2007 IEEE Aerospace Conference talks about developing robotics that will be the next generation of "entry, descent, and landing (EDL) systems". This mission was to be conducted by the Mars Science Laboratory (MSL). Essentially, the ESL will fly in the rover with more lift-to-drag ratio than ever before on Mars. Afterwards, it would deploy a parachute and perform sky crane maneuvers. We draw from this idea when creating the transport vehicle.

[14] Information is provided about SpaceX's SuperDraco engines used on Crew Dragon. The uses of these engines and the thrust capabilities of them are listed. The high thrust capability, the ability to restart, the little required maintenance between each flight, and the powered landing capabilities are why these engines are chosen.

[15] Information is provided on the weight of hydrazine tanks to account for refined weight calculations. One of the commenters states that "every kilogram of hydrazine will require about 0.05 kilograms of additional tank mass", which is accounted for in the weight calculations.

[16] This article delves into the various components of NASA's thermal system, which include radiators, surface coatings, multi-layer insulation, and heaters.

[17] This article gave the team inspiration to pursue are servo motor powered vehicle from the DST. The article talks about the innovations pursued by the French national space agency (CNES) to explore the moons of Mars.

[18] [19] These Wikipedia articles provided invaluable information about the engines that shall be implemented into the sky crane.

[20] These lecture slides provided insight on the structural analysis of spacecraft structures.

[21] This article references the X-band radio waves that will used for the communication between the DST and the EEV to power the servo motor.

[22] This article confirms that the X-band radio wave technology can be utilized at a greater distance than the current mission entails, which is promising.

[23] This article delves in the research of how the human body responds to being in space.

[24] This article delves further on the effects of space on the human body,

[25][32] This article talks about the stress distribution tests on an aexible wheel. It was determined that increasing the contact angle will decrease the stress on the wheels.

[26] This website provides invaluable information about N2O4/MMH, which will be utilized by the SuperDraco engines.

[27] This website provides details and schematics of the VIKAS engine, one of the potential engines.

[28] This website gives an in-depth explanation of hypergolic propellants, which include the advantages such as having a predictable thrust. This is invaluable information because it limits a source of error and causality.

[29] This article provides the schematics for the Aestus II engine, which is one of the candidates up for engine selection.

[30] This article is about the MR-80B engine which was utilized in NASA's original sky crane design. It was researched to draw a comparison to the current engine that will be used in SCOTT's design.

[31] This Wikipedia article investigates hypergolic propellant further, as it will be the propellant used in the SuperDraco.

5 Design

5.1 CAD designs

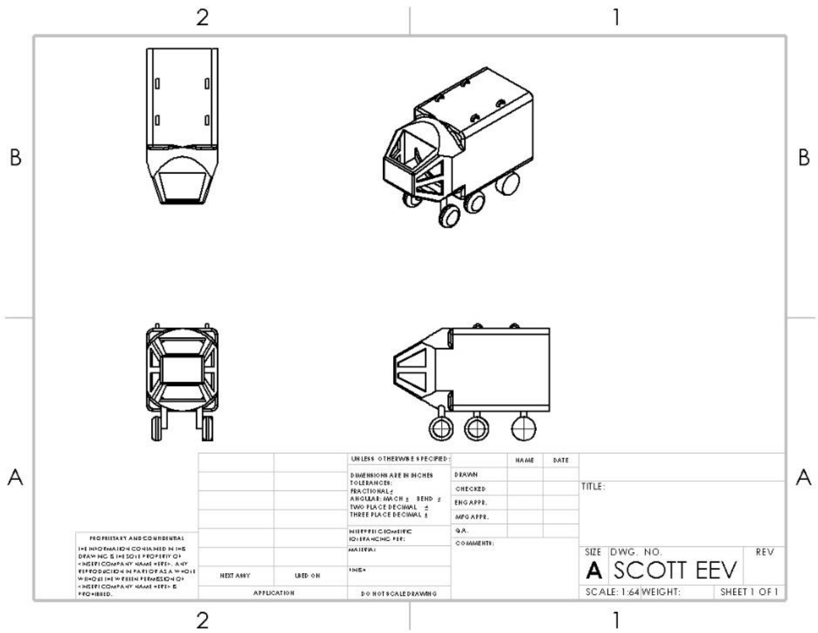


Figure 14. SCOTT's EEV

Figure 10, as shown above, was sketched by Andrew. The model was designed by Alejandro and drawn in Solidworks. The design drew inspiration from NASA’s EEV. The vehicle has three wheels on each side. It has a cabin in front and an area in the back for room for the living and research necessities.

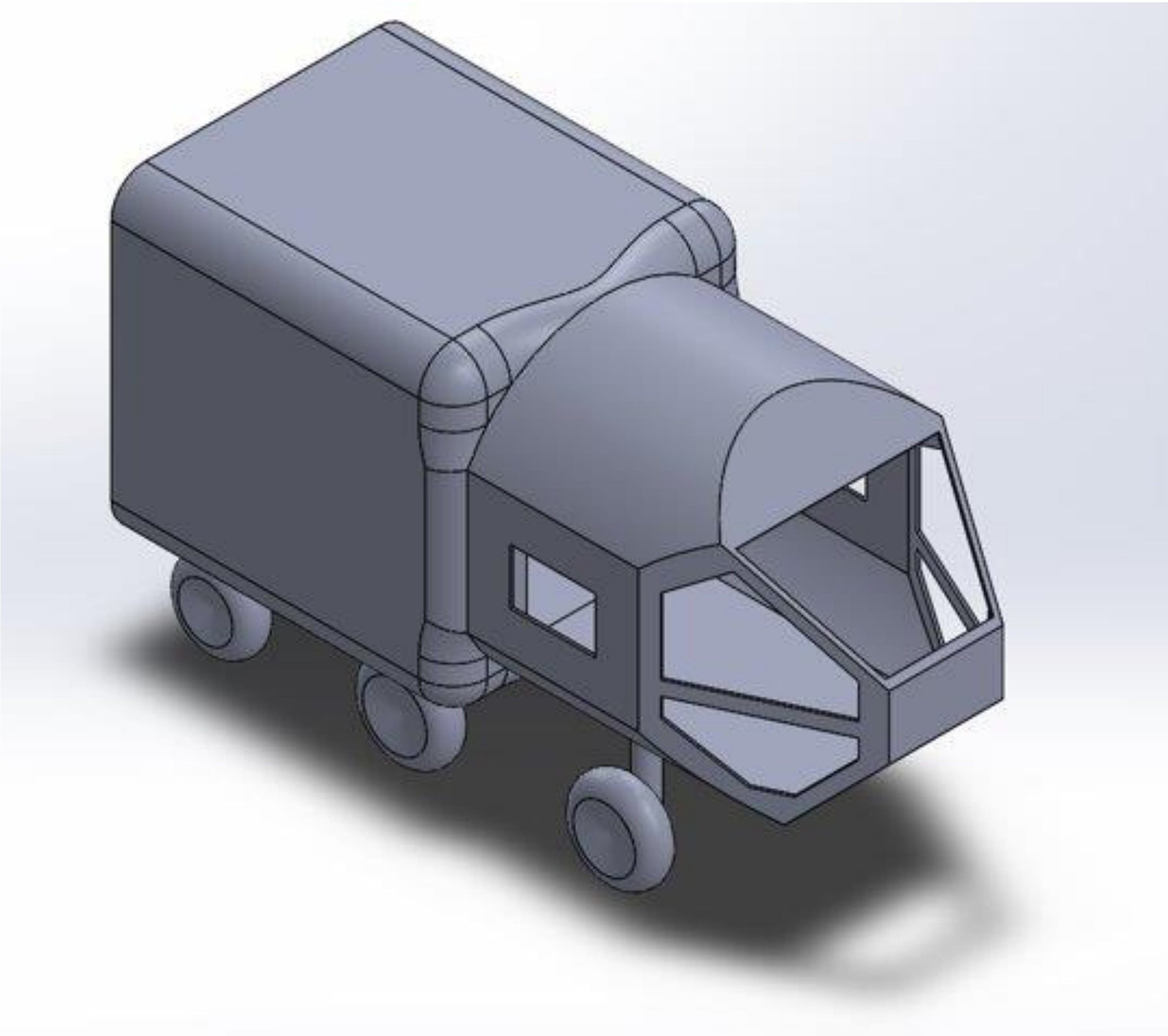


Figure 15. Initial CAD model of the EEV

The CAD model were completed by Alejandro, which provides a better idea of the design based off the hand drawings. The front wheel was moved over to underneath the cabin. Some considerations to consider are total weight, top speed, dimensions, propulsion systems, and electric motor, if applicable.

The launch vehicle that will be dejected from the DST is based off NASA's Sky Crane. The initial concept of how the EEV will be detached from the sky crane is via magnetic tethers. Some problems with this design are if the tethers dethatch mid-flight or if they are unable to attach again.

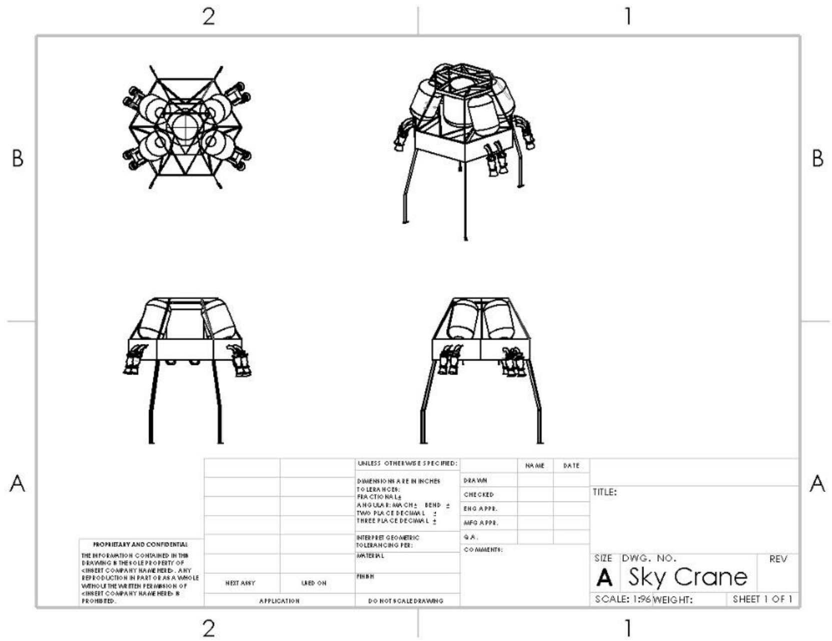


Figure 16. Sky crane attachment

Figure above shows how the sky crane will attach to the surface of the moon. It will have stilts that can dig into the surface to support the sky crane. They can subsequently be moved back onto the sky crane via a hydraulic component.

Figure 17. Fully assembled CAD model of SCOTT

As shown above, the EEV is housed underneath the sky crane, and is held by a series of metal hooks. Once the sky crane lands, it will simultaneously release legs to rest on to await pickup of the EEV once the mission is completed. The hooks on the sky crane will attach and detach hydraulically to either lock the EEV in place or let it free on the moon.

5.2 Stress

Stress is a key parameter for structural designs. The stress was calculated for the legs that will be planted onto the Martian moon surface to allow the EEV to touch the surface. The total weight of the Sky Crane was determined to be 17155 pounds in another chapter 2. The assumption is the weight is evenly distributed along the four legs with a load of 4137.5 pounds. The legs are assumed to have a rectangular cross section. The results are shown below. The following equations were utilized.

Equation 2. Area

$$A = lw$$

Equation 3. Moment of Inertia for Rectangular cross-section

$$I = \frac{bh^3}{12}$$

Equation 4. Moment

$$M = Pd$$

Equation 5. Stress for the worst-case scenario

$$\sigma_{worst\ case} = \left(\frac{P}{A}\right) + \frac{M(\frac{h}{2})}{I}$$

The stress was assumed that normal stress and bending stress would act upon the leg, which is the worst-case scenario.

Table 4. Leg Stress

σ_L, leg stress assuming worst − case scenario	
W_T, total weight (lb)	17155.00
P, load on legs (lb)	4288.75
l, length (in)	120.00
w, width (in)	24.00
A. area (in^2)	2880.00
I, moment of inertia (in^3)	3456000.00
σ_a, axial stress (psi)	1.49
M (lb*ft)	257325.00
σ_b, bending stress (psi)	4.47
σ_T, total stress, worst − case (psi)	5.96

With the selected parameters, it was determined that total stress on the legs is 5.96 pounds per square inch, which is an insignificant amount of stress. The stress was considering that the legs would equally share the load of the total weight of the sky crane since it will be on the surface of the moon for a few days before the EEV returns. The legs will be made of a typical aluminum alloy with a compressive yield strength of 120 MPA, resulting in a factor of safety of over 20 million.

Another stress that should be considered would be the stress on the wheels of the EEV. While not many calculations were completed, there was a study found that was conducted on the surface of an flexible wheel using loads of 2, 3.5, 5 kilograms each. In the study, it was determined that increasing the contact angle decreases the normal stress on the wheels. This type of wheel is useful for moving loose soil by moving the "normal stress outside the area", which increases movement speed of the wheels [32].

Another stress that will be considered is the stress on the hooks since they will be holding onto the EEV. Using the following equations, the stress on the hook can be found. The analysis involves knowing the following parameters, inner radius, outer radius, center radius, neutral radius, eccentricity, force, moment, and area. Eccentricity can be found by subtracting the center radius from the neutral radius.

Equation 6. Eccentricity

$$e = r_c - r_n$$

Where rc is the center radius and rn is the neutral radius.

The stress can be found by using the following equation where y is the moment arm:

Equation 7. Hook Stress

$$\sigma = \frac{F}{A} + \frac{My}{Ae(r_n - y)}$$

The hook stress equations yield a stress of 103,157.71 psi, which is invaluable to determine the material needed to design the hooks with since the hooks will be carrying the EEV. The hooks will be made out of a typical steel where the yield stress is equal to 350,000,000 psi. The factor of safety for the hook stress is over 3000.

6 Sources of Technology

6.1 Energy Source Options

After careful consideration of all systems that will be used on the SCOTT it is important to choose an energy source that will suffice for all energy requirements. A few of these energy requirements stem from lighting, heating, and handling of the rover. With these energy requirements in mind an energy source with a high output of power is necessary. A few considerable sources of energy, as seen in other space flight vehicles are solar energy, nuclear energy, and batteries. Each has their perspective advantages and disadvantages.

Beginning with solar power sources the advantages are taken into consideration. The first known advantage is large peak power levels which allow for radars to achieve better range []. The main technology used in solar panels is photovoltaic technology. The following are advantages of solar panels. Safe materials used in solar panels which are of ready use and abundance on earth. The disadvantages can be seen in missions which are further from Earth. When traveling further from earth the available solar light begins to dwindle. In this case solar panel utilization and productivity begin to be a reliability. In the case of the Mars surface, an issue that rose was the collection of dust on the solar panels. In this situation, there was a lack of sunlight able to hit the surface of the panels. Luckily, since Mars has an atmosphere and certain wind conditions, the dust would partially be blown off. When considering the moon's surfaces, dust may not be much of a barrier, but the available sunlight may prove solar panels to be of ineffective use.

The next power source option is a nuclear energy source which uses radioisotope thermoelectric generators to produce power. Nuclear forms of energy sources are common amongst deep space probes. These technologies contain pellets of radioactive material which produce heat from radioactive decay. The change of heat source to electric source is confirmed by the utilization of thermocouples. The one of few benefits when looking at nuclear energy is the simple parts and configurations used to produce the energy. When considering the essence of nuclear radiation, safety becomes a big concern in providing a safe enclosure for the radioactive material.

When considering the advantages of both nuclear energy and solar energy the benefits from both energy sources seem to outweigh the negatives. The decision for both energy sources to be implemented has been made. In this case, as for most deep space and near-earth voyages passive and active energy sources are required. When considering the distance of the moons from the sun and the total sunlight the moons receive, solar panels only prove to be useful when the sun is hitting the solar panels for which produce passive energy. Passive energy is essentially a system for which it is not reliant on exterior energy sources other than the sun. For this reason, solar panels are more often a desired energy source. As for nuclear energy, safety measures are of concern. Considering the distance from the sun though, an active energy source such as nuclear energy is needed. An active energy source is a system in which the energy provided is essentially from an interior source of the complete system.

When constructing the active energy source of nuclear energy, the focus is brought to the safety of the system. Although nuclear energy sources on manned missions have been of little use throughout the history of manned missions, there are few examples such as Apollo 13 which utilized a nuclear energy source. Even though the mission was a failure, the component which failed was not the nuclear energy source but an oxygen tank in the service module. The need for analysis and a complete understanding of the nuclear system that will be attached to the rover is necessary.

To understand the nuclear energy system, analysis is performed on the chosen material which is Plutonium-238. Plutonium-238 provides about 500 watts per kilogram of thermal power [37]. When looking at the energy needs of the rover, and power output of 2.5 kW would be needed to match the power consumption for the battery package that will be implemented on the rover. This conversion of 2.5 kW is about 5 kg which is about 11 lbs. of Plutonium-238. Looking at Plutonium-238 which is a hazardous material, it must be understood that Plutonium-238 is more so hazardous when consumed or inhaled by humans. Plutonium-238 is known to emit alpha particles which are very easy to stop. Even when considering the dangers of Plutonium-238 are more so deliberate actions instead of passive radioactive hazards, safety measures must be taken. The first safety measure to be taken is encasing the Plutonium-238 in an iridium metal cladding. The second safety measure to be taken is encasing the iridium metal cladding in several layers of high temperature graphite [37]. Lastly, the casing is then placed in an aeroshell which ensures the casing does not burn off in the presence of a high heat environment. Below is a diagram of the complete casing for the Plutonium-238 energy source.

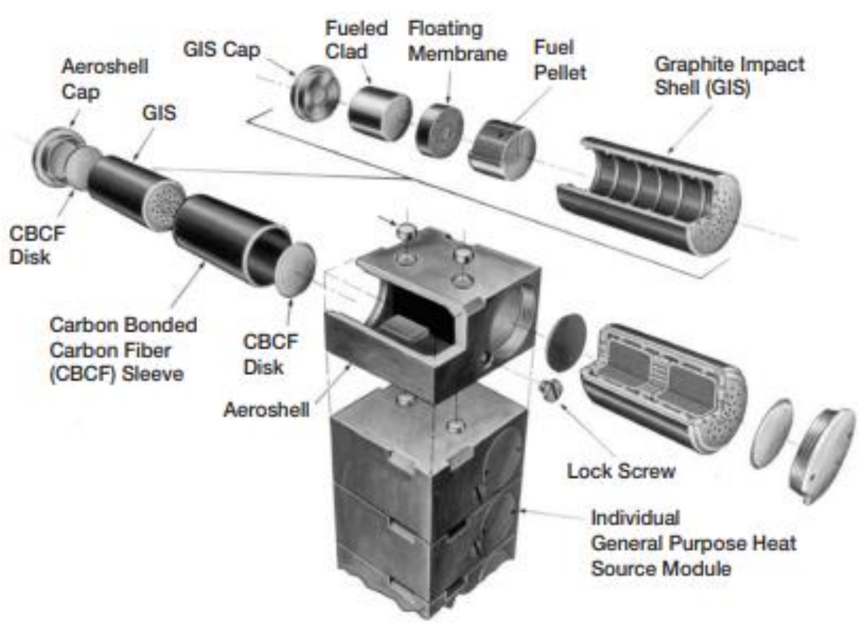


Figure 18. Complete casing for Plutonium-238 energy source [36]

The next energy source to be analyzed is solar panels. Similar to the International Space Station (ISS) and other rovers that have visited the surface of Mars, the EEV will utilize solar panels as a power source as well. First the solar panels that will be used must be analyzed. Like the solar panels used on the ISS, the solar panels used on the EEV consist of thousands of solar cells that are made from purified chunks of silicon. The cells directly convert light to electricity using photovoltaics [35]. The solar panels will be controlled by gimbles which continuously direct the surfaces of the solar panels at the sun. For design requirements, a recommended power output of 1 kW to recharge the battery pack is used. This determination is calculated relating the surface area of the solar panels on the ISS to the power outputs of the solar arrays. Below, a relation is made to determine the surface area needed to produce 1 kW of power from the solar arrays that will be attached to the EEV.

$$\frac{120\ kW}{27{,}000\ ft^2} = \frac{1\ kW}{(X)}$$

Solving for (X)

$$(X) = \frac{(1\ kW)(27{,}000\ ft^2)}{120\ kW}$$

$$(X) = 225\ ft^2$$

On the left side of the relation, the ratio of peak power output to surface area is related to the right side of the relation to determine the surface area required to produce 1 kW of power. After the calculations have been made it can be seen the total surface area needed to produce 1 kW of power is 225 ft^2.

Radiation based technology will be implemented to heat the EEV. Such technologies include coating the vehicle black to allow more absorption of solar energy to heat the vehicle. Insulation, radiators, and heaters will be implemented as well [16].

6.2 Control Systems

After doing in-depth research on space orbiter & rocket booster detachment controls, it led to some extensive research regarding motors, detection devices, & their control. With the simple hydraulic motor-controlled hook attachment/detachment method that was in mind, the next step was to dive into wireless motor controls. After extensive research on that it had been decided for efficiency purposes that it would be best if the sky crane was 100% controlled from the DST via **servo-arduino motors.**

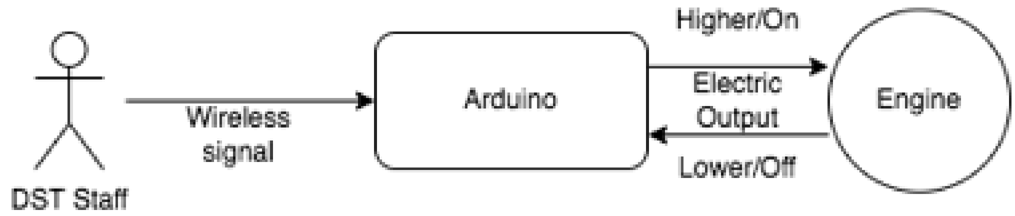


Figure 19. System Block for Arduino Engine

According to [21], servo motors are a very popular choice for controlling SpaceX's powerful rockets & NASA controlling their Mars rovers. Therefore, the sky crane will be powered by DST staff via controlling the crane's servo motor-controlled thrust. Each engine on the sky crane will be equipped with a servo motor along with a wireless arduino that can power additional servo motors that would change the angle of any of the engines for ease of flight navigation. In addition, the EEV hook attachment/detachment will be done by the technology of servo motors as well. This brings simplicity to the mission crew having the only responsibility of EEV control once detached on the moons.

Figure 20. System Block for Hook Detatchment

According to [8], the EEV that is being inspired from for this development will be **electric battery powered**. Therefore, the mission crew will drive the vehicle via the same technology used to power Teslas. According to [22], verbal communication between the DST staff & mission crew will be done via "X-Band radio waves" which are like antennas that perform like walkie talkies. The DST staff will also be able to monitor & perform proper navigation via monitoring the velocity with doppler data.

X-Band radio waves data is the modern-day technology used for communications between earth & mars which is sustainable enough for between the DST & moons with the current capability of sending 500 kilobits per second. With closer distance, the signal strength is much greater enabling the ability to perform more communications, ensuring the liability & safety of the mission crew.

6.3 EEV Motor System

According to [33], Teslas produce 180.5 kW of power from the front motor. Which directly correlates to the same amount the EEV will use when its motor sources power from the battery. According to [34], the way the battery communicates power to the motor to generate, electrochemical reactions in the lithium-ion cells create electricity. That electricity flows through power electronics that control the voltage and current, then it flows to electromagnets in the motor that create powerful magnetic fields rotating the shaft to turn the wheels. The power required to rotate this shaft has the most correlation to traditional measures of horsepower. However, the chain begins in the electrochemical reactions that happen in the battery pack. Depending on the battery's temperature, state of charge and age, the amount of electricity extracted can vary widely.

6.4 External Thermal Control System Design and Operation

When thinking of energy sources, thermal energy and heat transfer arises. For all components to work and for astronauts to be able to live in the rover vehicle the internal environment and systems used on the rover require adequate amounts of heat transfer. This noted analysis has been conducted in determining the most reliable and adequate form of thermodynamic process to perform heat transfer. As an initial reference, the International Space Station's process of ensuring heating systems and cooling systems have been evaluated for means of implementing similar processes on the rover.

When looking at the design requirements for the thermal system, the conditions and requirements for the system must be understood. The first of these conditions would be the environmental conditions for which the system will be working in. The first of the conditions is the surface temperature of both moons. The surface peak temperature of Phobos is during the day on the sunlit lunar surface at –4 degrees Celsius. The lowest temperature on the surface of the moon being on the dark side of the moon is -112 degrees Celsius. Deimos also experiences the same surface temperatures. The next characteristic of the environment is the amount of radiation on the surfaces of the moons stemming from the sun. When considering the duration of the mission there are a few instances of time where the rover and crew will be experiencing different amounts of radiation. A study has been considered for which different orbits and the percentage of radiation of these orbits have been accounted for. Seen in table below are the percentages compared to free space for which solar radiation is determined.

Table 5. Solar Radiation with respect to orbit

Location	Roundtrip Transfers		Station-keep	Effective Dose Equivalent (mSv/day)			
	Delta-V (m/s)	Time (hrs)	Delta-V per Day	1977 Solar Min	1991 Solar Max	Percent of Free Space	
Free Space				0.826	0.399	100.0%	100.0%
L1 (1- 10 m Position Error)	7.9	3.7	0.22 - 1.30	0.623	0.300	75.3%	75.3%
L4/L5	64.0	141	Very Low	0.798	0.385	96.6%	96.6%
20 km DRO	24.6	4.1		0.763	0.368	92.4%	92.4%
150 km DRO, 0 incl.	63.8	10.0		0.797	0.384	96.4%	96.4%
150 km DRO, 10 deg incl.	76.9	10.9					
200 km DRO, 0 incl.	82.1	10.1		0.798	0.385	96.5%	96.5%
200 km DRO, 10 deg incl.	99.4	11.0					
Phobos Surface				0.401	0.196	48.5%	49.1%
Phobos Surface w/ 10 deg Crater Rim				0.326	0.159	39.4%	39.9%
Mars Surface				0.332	0.173	40.2%	43.3%
Lunar Surface				0.430	0.210	52.0%	52.7%

When looking at the table above there are a few determinations that have been made. The first of these determinations is that these numbers are identical for both moons of Mars. Therefore, the percentage of free space radiation would be taken at a point of maximum radiation for which Mars and both moons block 0% of the radiation stemming from the Sun. As well as radiation at the surface of both moons where radiation from the sun is taken at a percentage of maximum free space radiation which is about 48.8%.

7 Orbital Mechanics Analysis and Trajectory

The trajectory and timing of the spacecraft is arguably the most crucial part of the mission. Efficient maneuvering between orbits must occur in order to use as less fuel as possible while traveling from one orbit to another in a timely manner. Two different orbital transfer methods will be considered and analyzed. The two methods are the *Hohmann transfer* and the *Bi-elliptic transfer*. These transfer methods are recognized as the two most fuel-efficient orbital transfers. The optimal method will be determined by comparing the required velocity changes and the time of flight for each method.

Three orbital transfers are required for this mission.

1. Parking Orbit to Deimos
2. Deimos to Phobos
3. Phobos to Parking Orbit

7.1 Hohmann Transfer

The Hohmann transfer is the simplest and often the most fuel-efficient transfer method. This method can be used to transfer between two circular orbits by creating an intermediate elliptical orbit that connects the two circular orbits. Deimos and Phobos do not have perfectly circular orbits; however, the eccentricities of the orbits are so close to zero that a circular orbit is an accurate approximation to make. Therefore, the Hohmann transfer method easily applies to this case.

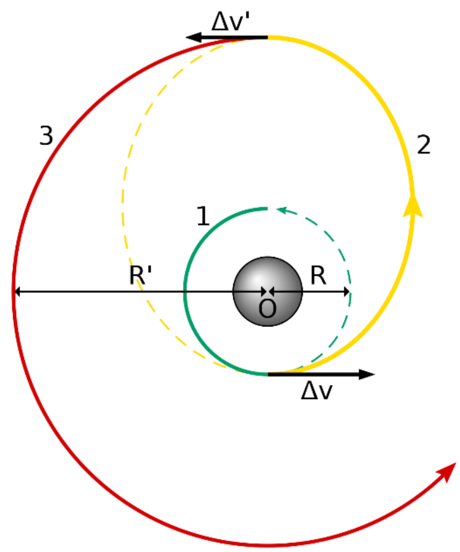


Figure 21. Hohmann Transfer Diagram

A typical Hohmann transfer is seen in the figure above. This method requires two burns to occur at either the periapsis or apoapsis for every orbital transfer. The ΔV calculations are derived from the conservation of mechanical energy.

The specific mechanical energy for every orbit is constant and is equal to:

Equation 8. Specific Orbital Mechanical Energy

$$\xi = (\text{Kinetic Energy/Mass}) + (\text{Potential Energy/Mass})$$

The kinetic energy per unit mass is simply equal to $V^2/2$. The potential energy per unit mass is defined as the standard gravitational parameter (μ) divided by the height of the satellite at any given time: (μ/r)

Equation 9. Specific Orbital Mechanical Energy

$$\xi = (V^2/2) + (\mu/r)$$

The standard gravitational parameter is equal to Newton's gravitational constant multiplied by the mass of the central body. For this mission, the central body is always Mars.

Equation 10. Standard gravitational parameter

$$\mu_{\text{Mars}} = 4.282837 * 10^{13}\ m^3/s^2$$

The first ΔV equation to transfer from the bigger circular orbit to the smaller orbit is simply the velocity of the bigger circular orbit minus the velocity of the transfer elliptical orbit:

Equation 11. First Transfer ΔV

$$\Delta V_1 = V_{CS1} - V_1$$

The velocities of the elliptical orbit and circular orbit are given by:

Equation 12. Elliptical Orbit ΔV

$$V_{elliptical} = \sqrt{2(\frac{\mu}{r} + \xi)}$$

Equation 13. Circular Orbit ΔV

$$V_{circular} = \sqrt{\frac{\mu}{r_1}}$$

In total, the first change of velocity required to get to smaller circular orbit is given by:

Equation 14. Total ΔV to get to the smaller orbit

$$\boldsymbol{\Delta V_1 = \sqrt{\frac{\mu}{r_1}} - \sqrt{2(\frac{\mu}{r_1} + \xi_t)}}$$

This occurs at the apoapsis of the transfer orbit.

The second ΔV occurs at the periapsis of the transfer orbit and is given by:

Equation 15. Second ΔV

$$\Delta V_2 = V_2 - V_{CS2}$$

This is the same principle as the first equation; however, the circular orbit velocity is subtracted from the transfer orbit velocity and it is a function if the smaller orbit radius instead of the bigger orbit radius.

In total, the second change of velocity required to fully complete the Hohmann transfer is:

Equation 16. Second ΔV to complete the Hohmann transfer

$$\boldsymbol{\Delta V_2 = \sqrt{2(\frac{\mu}{r_2} + \xi_t)} - \sqrt{\frac{\mu}{r_2}}}$$

where $\boldsymbol{\xi_t = \frac{-\mu}{r_1 + r_2}}$

Orbital information used in this analysis are given below for all three required orbits in this mission.

Table 6. Orbital Information for Parking Orbit, Deimos, and Phobos.

Hohmann Transfer Orbits				
Orbit	**Semi-Major Axis (km) (Radius)**	**Circular Orbit Velocity (m/s)**	**Orbital Period (hrs)**	***Eccentricity**
Parking	59790.3	846.4	123.3	0
Deimos	23463.2	1351.1	7.64	0.0002
Phobos	9376.0	2137.3	30.31	0.0151

The eccentricity of a circular orbit is equal to zero. It is important to note how closely these orbits resemble a circular orbit. The Hohmann transfer method is valid because of these eccentricity values. It is assumed the parking orbit where the mission begins is in a perfectly circular orbit for simplicity.

It is also important to determine the time of flight for each transfer. Since the mission to both moons and back must be completed within 30 days, a timely transfer is desired in order to maximize the amount of time spent on each moon. The time of flight of an elliptical orbit, derived from Kepler's Third Law is given by:

Equation 17, Kepler's Law

$$\mathrm{TP} = 2\pi\sqrt{\frac{a_t^3}{\mu}}$$

The time of flight of the transfer elliptical orbit is half of the total period:

Equation 18. Time of flight of the transfer for the elliptical orbit

$$\mathbf{TP_t} = \boldsymbol{\pi}\sqrt{\frac{\boldsymbol{a_t^3}}{\boldsymbol{\mu}}}$$

where a_t is the semi-major axis of the transfer orbit. It is equivalent to $\frac{r_1+r_2}{2}$.

The table below summarizes the results of the Hohmann transfer method.

Table 7. Hohmann Transfer Analysis Results

Hohmann Transfer Results					
Calculation Step	Description	ξ of the transfer orbit (m^2/s^2)	ΔV (m/s)	TPt (hrs)	TPt (days)
1	1st Burn from Parking Orbit to Deimos Transfer Insertion	-514432.99	210.9	35.8	1.49
2	2nd Burn from Deimos Transfer to Deimos Orbit	-514432.99	268.2		
3	1st Burn from Deimos Orbit to Phobos Transfer Insertion	-1304184.33	330.1	5.68	0.24
4	2nd Burn from Phobos Transfer to Phobos Orbit	-1304184.33	417.6		
5	1st Burn from Phobos Orbit to Parking Orbit Transfer Insertion	-619208.23	673.0	22.3	0.93
6	2nd Burn from Parking Transfer to Parking Orbit	-619208.23	405.7		
7	**Total**		**2305.5**	**63.78**	**2.66**

The Hohmann transfer method gives us a total velocity change of 2305.5 m/s and a minimum travel time of 2.66 days.

7.2 Bi-Elliptic Transfer

A bi-elliptic transfer uses two different elliptical orbits to transfer from one orbit to another. This method requires one more burn than the Hohmann method. Even though an extra burn is required, some bi-elliptic transfers require less change in velocity than the standard Hohmann transfer. A typical bi-elliptic transfer is given in the figure below.

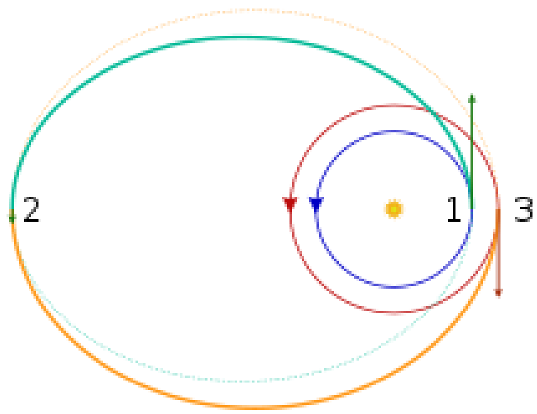


Figure 22. Typical Bi-Elliptic Transfer

The first burn shoots the spacecraft into a large half-elliptical orbit, where the second burn occurs at the apoapsis to put the spacecraft into a larger half-elliptical orbit that meets the target destination. At the periapsis of the second elliptical orbit, a third burn occurs in the opposite direction to put the spacecraft fully in the desired orbit.

For this case, a shortcut can be taken for the initial transfer from parking orbit to Phobos. The order of moons visited will change so the smaller orbit is traveled to first. Instead of assuming the spacecraft starts in a circular parking orbit, it can be assumed the spacecraft starts in a elliptical orbit that is ready for a bi-elliptic transfer that will only require one burn at position 3.

The new orbital information for this method is given by the table below.

Bi-Elliptic Transfer Orbits				
Orbit	Semi-Major Axis (km) (Radius)	Circular Orbit Velocity (m/s)	Orbital Period (hrs)	Eccentricity
Parking	59790.3	Depends on position	123.3	0.918
Deimos	23463.2	1351.1	7.64	0.0002
Phobos	9376.0	2137.3	30.31	0.0151

Table 8. Bi-Elliptic Orbital Information

The ΔV equations for all three burns are again derived from the conservation of mechanical energy. The mechanical energy is constant for any orbit. The kinetic and potential energies fluctuate, but their sum remains the same at any position in the orbit.

<u>1st Burn</u>

Equation 19. 1st Burn

$$\Delta V_1 = \sqrt{\frac{2\mu}{r_1} - \frac{\mu}{a_1}} - \sqrt{\frac{\mu}{r_1}}$$

<u>2nd Burn</u>

Equation 20. 2nd Burn

$$\Delta V_2 = \sqrt{\frac{2\mu}{r_b} - \frac{\mu}{a_2}} - \sqrt{\frac{2\mu}{r_b} - \frac{\mu}{a_1}}$$

<u>3rd Burn</u>

Equation 21, 3rd Burn

$$\Delta V_3 = \sqrt{\frac{2\mu}{r_2} - \frac{\mu}{a_2}} - \sqrt{\frac{\mu}{r_2}}$$

<u>Time of Flight (Derived from Kepler's Third Law)</u>

Equation 22. Time of Flight derived using Kepler's Third Law

$$TP_t = \pi\sqrt{\frac{a_1^3}{\mu}} + \pi\sqrt{\frac{a_2^3}{\mu}}$$

Where, r_1 = initial circular orbit

r_2 = final circular orbit

r_b = common apoapsis

$a_1 = \frac{r_1+r_b}{2}$

$a_2 = \frac{r_2+r_b}{2}$

For the initial transfer form parking orbit to Phobos, only the third burn is required since they already share a common apoapsis.

Orbital Maneuvers for Bi-Elliptic Transfer Method

One burn from Parking Orbit to Phobos

Maximum of three burns from Phobos to Deimos

Maximum of three burns from Deimos to Parking Orbit

The bi-elliptic transfer introduces a free variable (r_b) that is not defined in the mission. Excel is used to find the optimal r_b value that produces the smallest ΔV. The excel spreadsheet used for these calculations are found in the appendix.

The results of the bi-elliptic transfer method is summarized in the table below.

Table 9. Bi-Elliptic Transfer Analysis Results Summary

Bi-Elliptic Transfer Results			
Calculation Step	**Description**	**ΔV (m/s)**	**TPt (days)**
1	Parking Orbit to Phobos Orbit	764.4	2.57
2	Phobos Orbit to Deimos Orbit	747.7	1.00
3	Demios Orbit to Parking Orbit	479.1	4.06
4	**Total**	**1991.2**	**7.63**

This method offers a total change of velocity equal to 1991.2 m/s and a minimum travel time of 7.63 days.

7.3 Hohmann Transfer vs. Bi-Elliptic Transfer

Table 10. Orbital Transfer Comparison

Orbital Transfer Comparison		
Transfer Type	**ΔV (m/s)**	**Time of Flight (days)**
Hohmann	2305.5	2.66
Bi-Elliptic	1991.2	7.63

The bi-elliptic transfer method offers a much more fuel-efficient journey; however, it takes a significant amount of time longer than the Hohmann transfer. Therefore, there is a trade-off between fuel used and time spent on each moon. By saving on fuel using the bi-elliptic method, about five days on lost on the moons collecting samples and performing experiments. Because of this, the Hohmann transfer method will be used to maximize the amount of time spent on the moons.

8 Propulsion

8.1 Engine Selection and Design

The engines used on the spacecraft will be SpaceX's SuperDraco engines. This engine was selected based on its thrust capability, specific impulse, and low thrust to weight ratio. Each engines is capable of producing around 73 kN of thrust. The maximum thrust required for this mission is around 29 kN. The sky crane will be equipped with eight SuperDraco engines.

These engines are assumed to be modified to fit the sky crane system. The modifications to the SuperDraco engines for this mission may result in a slightly different sizing, or added components, as compared with the current engines applied in a SpaceX setting. The thrust, mass fuel flow rate, fuel weight, and fuel tank size will be analyzed in the following sections. A more in-depth description of the engine selection is mentioned in Section 3.1.

8.2 Fuel Analysis

As the mission carries on, the spacecraft will expel fuel at every burn during the orbital maneuvering process as well as the takeoff and landing process. The spacecraft will also gain some weight on each moon due to the collection of samples. The exact weight of the spacecraft must be known during each step of the mission in order to accurately produce the amount of thrust that will successfully complete each orbital transfer.

The SuperDraco engines use a storable, hypergolic, propellant mixture composed of a monomethylhydrazine [$CH_3(NH)NH_2$] fuel and a dintrogen tetroxide [N_2O_4] oxidizer. Given the specific impulse of the engines and the required thrust, the amount of fuel used for every burn can be calculated. The specific impulse of an engine is directly related to the thrust and indirectly related to the mass flow rate of the fuel as given by equation 1:

$$I_{sp} = \frac{1}{g_0} \frac{F_{thrust}}{\dot{m}_{propellant}}$$

From the orbital transfer calculations in chapter 7 and an assumed burn time for each maneuver, the required thrust is found for each burn. The SuperDraco engines have a specific impulse of 300s. The table below summarizes the required force and fuel mass used at every burn.

Table 11. Weight Change for Each Orbital Burn

Description	ΔV (m/s)	Burn Time (sec)	Starting Weight (lbs)	Thrust (N)	Fuel Expended (lbs)	Ending Weight (lbs)
1st Burn from Parking Orbit to Deimos Transfer Insertion	210.9	120	17155	13688	1230	15925
2nd Burn from Deimos Transfer to Deimos Orbit	268.2	120	15925	16159	1451	14474
1st Burn from Deimos Orbit to Phobos Transfer Insertion	330.1	120	14474	18076	1623	12851
2nd Burn from Phobos Transfer to Phobos Orbit	417.6	120	12851	20304	1217	11634
1st Burn from Phobos Orbit to Parking Orbit Transfer Insertion	673.0	120	11634	29622	2659	8975
2nd Burn from Parking Transfer to Parking Orbit	405.7	120	8975	13776	1237	7738

From these calculations, it is determined that the fuel weight needed is the staring weight subtracted by the ending weight. Therefore, the total amount of fuel needed for this mission is 9417 lbs.

It is important to note that there is weight change for each moon mission. Additional fuel weight is lost during landing and takeoff. It is difficult to predict the exact amount of fuel needed to land because it depends on the conditions of the moon and the spacecraft trajectory. The spacecraft will need to adjust its position to land on stable, relatively flat ground. The spacecraft will also gain weight on the moons due to samples being collected. Because of this, a design assumption is made to set the weight lost equal to the weight gained on each moon mission.

8.3 Fuel Tank Sizing

The sky crane will need to be able to hold fuel tanks capable of carrying 9417 pounds worth of the hypergolic propellant mixture. The densities of monomethylhydrazine and dinitrogen tetroxide are known at 20°C. The temperatures of the fuels are assumed to be kept at this temperature throughout the duration of the mission. Since the mass of the total fuel and the densities of both fuels are known, the volume can be determined. The densities are listed in the table below.

Table 12. Fuel Volume Calculations

Required Fuel Volume							
Compound Function	Compound	Density @ 20C (kg./m^3)	Density in lbs/ft^3	Percentage of Fuel by Mass	Total Weight (lbs)	Fuel Portion (lbs)	Volume (ft^3)
Oxidizer	N2O4	1442.46	90.05	0.625	9417	5885.625	65.35952249
Propellant	CH3NH2	880	54.94	0.375	9417	3531.375	64.27693848

For a monomethylhydrazine and dinitrogen tetroxide propellant mixture, the monomethylhydrazine will be 62.5% of the mixture in terms of mass while dinitrogen tetroxide will be 37.5% of the mixture in terms of mass. The sky crane must have fuel tanks capable of storing 65.4 ft^3, or 489 gallons, of the oxidizer [N_2O_4]. It must also have separate fuel tanks capable of storing 64.3 ft^3, or 481 gallons, of the fuel [$CH_3(NH)NH_2$]. The design of the fuel tank has 5 tanks in total. There are four smaller tanks for the fuel, monomethylhydrazine, and one larger tank, located in the center, which contains the oxidizer, dintrogen tetroxide.

The larger oxidizer tank will be 489 gallons in volume. Each of the tanks for the fuel will be 120.25 gallons in volume.

Table 14. Oxidizer Fuel Tank Design Table

Oxidizer Tank Sizing		
Radius (ft)	Height (ft)	Volume (ft^3)
1	20.81747	65.4
2	5.204367	65.4
3	2.313052	65.4
4	1.301092	65.4
5	0.832699	65.4
6	0.578263	65.4
7	0.424846	65.4
8	0.325273	65.4
9	0.257006	65.4
10	0.208175	65.4
11	0.172045	65.4
12	0.144566	65.4
13	0.12318	65.4

Table 13. Fuel Tank Design Table

Fuel Tank Sizing (Each)		
Radius (ft)	Height(ft)	Volume (ft^3)
1	5.116831	16.075
1.1	4.228786	16.075
1.2	3.553355	16.075
1.3	3.027711	16.075
1.4	2.610628	16.075
1.5	2.274147	16.075
1.6	1.998762	16.075
1.7	1.77053	16.075
1.8	1.579269	16.075
1.9	1.417405	16.075
2	1.279208	16.075

Tables 13 and 14 give possibilities of tank sizing with a given volume. For the oxidizer tank, the chosen dimensions are a radius of 2 ft and a height of 5.2 ft. For the four smaller fuel tanks, the radius will be 1 ft and the height will be 5.1 ft.

9 Minimum Success Criteria

The minimum success criteria for The SCOTT is to ensure the safety of the crew during a round trip from Deimos and Phobos back to the DST. The SCOTT must be able to function properly for 30 days. The 30 days can flexibly be 1 to 10 days on each moon depending on the distance trade study ~revise this sentence after mission analysis is complete. The crew must be able to survive inside the vehicle during the duration of the excursion. The SCOTT must be able to hold the Martian material safely to prevent exposure to the crew. The sky crane component must be able to land, release the EEV, and be able to retrieve the EEV from each moon.

As for the life factors, it will be implemented using RIDGE.

R.I.D.G.E

R: Radiation Exposure

Key to prevention: Implement shielding, radiation monitoring, & specific operational procedures. NASA is developing new technology that would carefully monitor & characterize the radiation environment that would better monitor the radiation crew would be exposed to.

I: Isolation & Confinement

Key to prevention: On-going research NASA is currently doing but present-day factors to consider: frustration journaling & space gardening.

D: Distance from Earth (urgent help)

Key to prevention: All astronauts are properly trained to assist, help, & diagnose any medical-related situation during a mission.

G: Gravity fields

Key to prevention: Wearing compression cuffs on the thighs to keep blood in the lower extremities to counteract fluid gifts or negative pressure devices. Back pain is monitored by obtaining spinal ultrasounds, muscle size/bone density are assessed for deterioration using MRI & high-resolution imaging techniques, before/after mission. Astronauts must exercise 2 hours a day to keep their bones & muscles healthy. Resistive exercises are best.

E: Environments (Close & Hostile)

Key to prevention: NASA is using technology to monitor the air quality of the space station to ensure the atmosphere is safe to breathe and not contaminated with gases, such as formaldehyde, ammonia, and carbon monoxide.

10 Schedule

SCOTT: Martian EEV

Kennesaw State University
Project Lead: Kamyar

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart

Project Start: Thu, 1/13/2022
Display Week: 1

Jan 13, 2022 | Jan 20, 2022 | Jan 27, 2022

TASK	ASSIGNED TO	PROGRESS	START	END
Phase 1 Title				
Project Selection	All	100%	1/13/22	1/15/22
Project Conceptualization	All	100%	1/14/22	1/20/22
IDR PowerPoint	Andrew	100%	1/20/22	1/24/22
IDR Paper	Andrew	100%	1/16/22	1/25/22
Finalize IDR / Turn in	All	100%	1/25/22	1/26/22

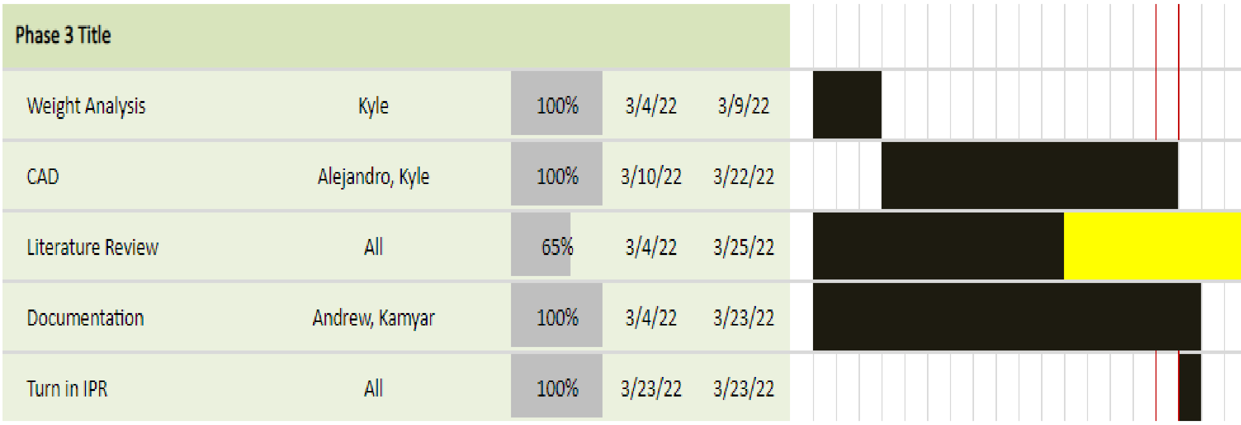
Figure 23. Schedule for the Project in Phase 1

The schedule for phase 1 included selecting the project, conceptualizing the project, creating the PowerPoint, creating the word document, and turning in the IDR, as shown in figure 10. All team members participated in selecting and conceptualizing the project.

Phase 2 PDR				
Tech and Budget Research	Kamyar and Andrew	100%	2/9/22	2/10/22
Past Projects Research	Kamyar and Kyle	100%	2/9/22	2/10/22
Gravity	Alejandro and Andrew	100%	2/10/22	2/13/22
Astodynamics	Kyle	80%	2/10/22	2/12/22
Fuel	Kyle	15%	2/10/22	2/12/22
Hand Drawings	Alejandro	50%	2/10/22	2/20/22
Documentation	Andrew/All	75%	2/10/22	2/22/22
Literature Review	All	85%	2/10/22	2/22/22
Finalize Decisions	All	100%	2/10/22	2/22/22
Turn in PDR	All	100%	2/23/22	2/23/22

Figure 24. Schedule for the Project in Phase 2

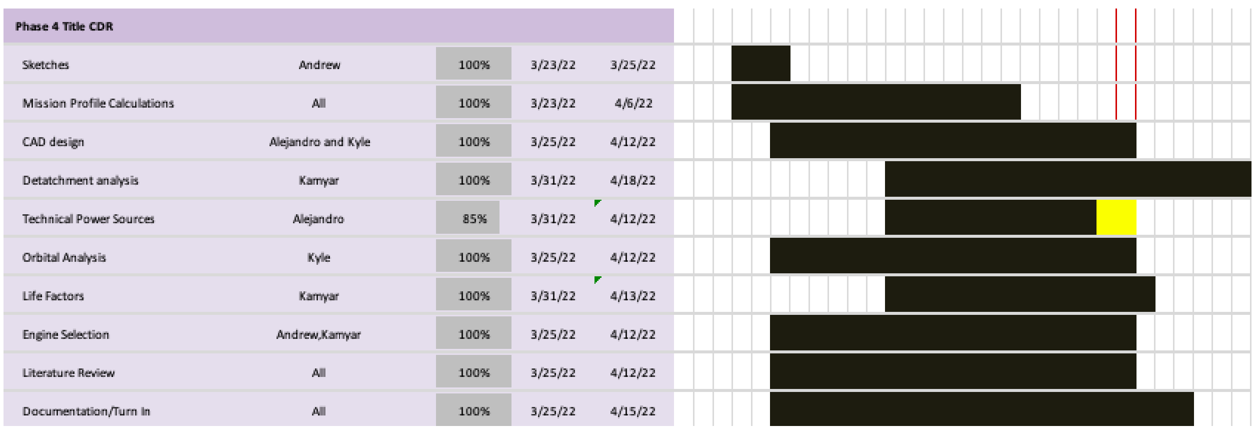
The schedule for phase 2 involved researching technology and budget, reviewing past projects, performing a variety of calculations, starting hand drawings, documentation, performing literature review, finalizing decisions on one EEV, and turning in the PDR, as shown in figure 11.



Phase 3 Title				
Weight Analysis	Kyle	100%	3/4/22	3/9/22
CAD	Alejandro, Kyle	100%	3/10/22	3/22/22
Literature Review	All	65%	3/4/22	3/25/22
Documentation	Andrew, Kamyar	100%	3/4/22	3/23/22
Turn in IPR	All	100%	3/23/22	3/23/22

Figure 25. Schedule for the Project in Phase 3

The schedule for phase 3 involved performing a weight analysis, creating a CAD model for the lander, continuing literature review, documenting the process, and turning in the PDR, as shown in figure 12.



Phase 4 Title CDR				
Sketches	Andrew	100%	3/23/22	3/25/22
Mission Profile Calculations	All	100%	3/23/22	4/6/22
CAD design	Alejandro and Kyle	100%	3/25/22	4/12/22
Detatchment analysis	Kamyar	100%	3/31/22	4/18/22
Technical Power Sources	Alejandro	85%	3/31/22	4/12/22
Orbital Analysis	Kyle	100%	3/25/22	4/12/22
Life Factors	Kamyar	100%	3/31/22	4/13/22
Engine Selection	Andrew,Kamyar	100%	3/25/22	4/12/22
Literature Review	All	100%	3/25/22	4/12/22
Documentation/Turn In	All	100%	3/25/22	4/15/22

Figure 26. Schedule for the Project in Phase 4

The schedule for phase 4 included the bulk of the analyses for the design of SCOTT with factors considered such as orbital and life factor analysis.

11 Budget

The budget for the entire design of the SCOTT should not cost more than $1 Billion. The cost of major items will be researched further. Furthermore, the sponsors of the project will be taken into heavy consideration. After careful consideration and review of the previous semester's group project, it was determined that the group was able to obtain a budget of $912 million including a launch vehicle from Earth to the DST.

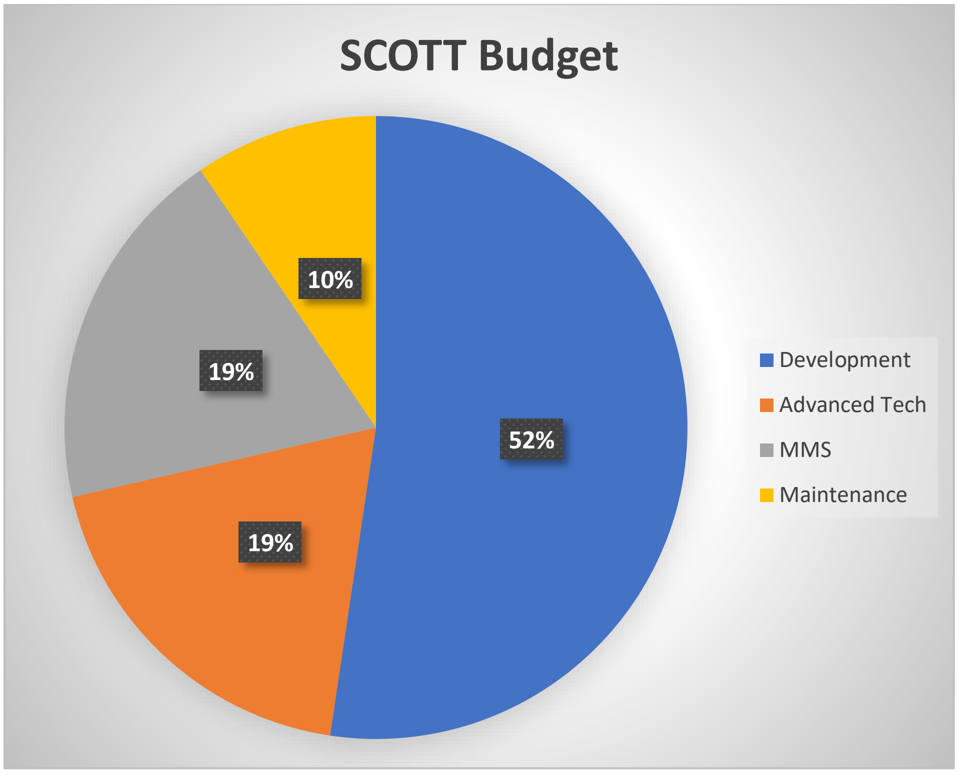


Figure 27. SCOTT Budget Breakdown

Given that the project states that SCOTT will be already in Martian Orbit, it was decided that their budget would be modified to aim for saving $2 million. One percent of the budget will be taken from the Mars Moon Mission and Advanced Technology Segments to increase the Development budget by two percent. The budget can be broken down and shown in figure 10 and tables 10-11.

Table 13. SCOTT Budget Breakdown by numbers

Total	$	910,000,000
Development	$	500,000,000
Advanced Tech	$	182,000,000
MMS	$	182,000,000
Maintenance	$	91,000,000

The table above is a breakdown of the pie chart above in figure 13. As shown above, the development of SCOTT will cost roughly $500,000,000. Advanced technology development and implementation will cost about $182,000,000. The moon mission itself will cost the same as advanced technology. Last, maintenance will cost around $91,000,000.

Table 15. SCOTT Budget Breakdown by Segments

Budget Breakdown	
Development	$ 500,000,000
Communications	$ 4,550,000
Facilities	$ 18,200,000
Equipment	$ 100,100,000
Logistics	$ 91,000,000
Product Assurance	$ 18,200,000
Flight and Ground Software	$ 113,750,000
Integration and Test	$ 113,750,000
Cumalative Management	$ 9,100,000
Error Costs	$ 72,800,000
Advanced Tech	$ 182,000,000
Solar Panels	$ 54,600,000
Capsule/Transporter	$ 45,500,000
Life Factor Supplies	$ 27,300,000
Scientific Equipment	$ 54,600,000
Moon Mission	$ 182,000,000
Propulsion/Fuel Consumption	$ 40,950,000
Ground/Emergency Support	$ 910,000
Avionic Costs	$ 21,840,000
Electrical Power System	$ 18,200,000
DST Launch/Operational Support	$ 9,100,000
Maintenance	$ 91,000,000
Maintenance	$ 36,400,000
Government Labor	$ 9,100,000
Contract Labor	$ 45,500,000

Table 11 is a breakdown of the SCOTT budget by segments. A majority of the budget will go into development of communications, facilities, equipment, product assurance, flight and ground software, integration and testing, cumulative management, and error costs. Advanced technologies will be tied for total costs with the moon mission segment. Finally, the maintenance of SCOTT will take up the least of the budget. As shown from the table, the majority of the budget will be allocated to the development of SCOTT.

12 Results

The spacecraft will consist of a rover attached to a rocket powered sky crane by a series of hooks. The sky crane is the propulsive transporter which will transfer the rover from the original orbit to each moon and back. The following analyses facilitate the design of the mission and spacecraft.

Orbital Mechanics/Astrodynamics

An orbital mechanics analysis was performed to find the optimal trajectories, change of velocity, thrust, and time of flight. The Hohmann Transfer method and the Bi-Elliptic Transfer method were compared and summarized in the figure below.

Table 16. Orbital Mechanics Comparison Results

Orbital Transfer Comparison		
Transfer Type	**ΔV (m/s)**	**Time of Flight (days)**
Hohmann	2305.5	2.66
Bi-Elliptic	1991.2	7.63

The Bi-Elliptic method is more cost effective and requires less thrust; however, it requires an extra five days of orbital travel time. The Hohmann transfer method was selected in order to maximize time spent on the moons. The orbital trajectory was modeled and simulated using NASA's General Mission Analysis Tool (GMAT). The spacecraft will require a total change of velocity of 2305.5 m/s and will spend 2.66 days in orbital travel. A maximum thrust of 29,622 N is required.

Weight/Fuel

Table 17. Fuel Analysis Results

Weight Change Due to Fuel						
Description	**ΔV (m/s)**	**Burn Time (sec)**	**Starting Weight (lbs)**	**Thrust (N)**	**Fuel Expended (lbs)**	**Ending Weight (lbs)**
1st Burn from Parking Orbit to Deimos Transfer Insertion	210.9	120	17155	13688	1230	15925
2nd Burn from Deimos Transfer to Deimos Orbit	268.2	120	15925	16159	1451	14474
1st Burn from Deimos Orbit to Phobos Transfer Insertion	330.1	120	14474	18076	1623	12851
2nd Burn from Phobos Transfer to Phobos Orbit	417.6	120	12851	20304	1217	11634
1st Burn from Phobos Orbit to Parking Orbit Transfer Insertion	673.0	120	11634	29622	2659	8975
2nd Burn from Parking Transfer to Parking Orbit	405.7	120	8975	13776	1237	7738

Based on previous mission history, design requirements, and design calculations and assumptions, a starting weight of 17,155 lbs is determined. The mass of fuel used for every maneuver is calculated in the table above. The spacecraft will require 9417 lbs of fuel to complete the mission. The ending weight when the spacecraft completes the mission is 7738 lbs. This is considered the payload. The payload to takeoff ratio is 0.45. 55% of the takeoff weight is fuel.

The sky crane will hold five tanks of either fuel or oxidizer. The large oxidizer tank is designed to be 4 ft in diameter and 5.2 ft tall. It will hold 489 gallons of the oxidizer dinitrogen tetroxide. The four fuel tanks will each be 2 ft in diameter and 5.1 ft tall. All four of these combined will hold 481 gallons of the fuel monomethylhydrazine. The total volume of fuel/oxidizer is 970 gallons.

Stress

The two main stress concerns were the legs on the sky crane and the hooks which attach the sky crane to the EEV. Both stress analyses produced favorable results with large factors of safety. The hook stress had a factor of safety of over 3000 and the leg stress had a factor of safety of over 20 million.

Table 18. Stress Analysis Results

$\sigma_L, leg\ stress\ assuming\ worst-case\ scenario$	
$W_T, total\ weight$ (lb)	17155.00
P, load on legs (lb)	4288.75
$l, length$ (in)	120.00
$w, width$ (in)	24.00
$A. area\ (in^2)$	2880.00
$I, moment\ of\ inertia\ (in^3)$	3456000.00
$\sigma_a, axial\ stress$ (psi)	1.49
M (lb*ft)	257325.00
$\sigma_b, bending\ stress$ (psi)	4.47
$\sigma_T, total\ stress, worst-case$ (psi)	5.96

13 Conclusion

After careful study and analysis, the SCOTT EEV has a grand total budget of $912 million. The SCOTT will utilize the SuperDraco engines to power its thrust. The vehicle is a two part system composed of a two-man rover and a rocket powered sky crane transporter. The Hohmann transfer will be the orbit transfer method to maximize efficiency of the time spent traveling to and from each of the Martian moons. It was determined that the initial total weight of SCOTT will be 17155 lbs with a payload to takeoff ratio of 0.45. The SCOTT will return to the DST with a total weight of 7738 lbs.

For thermal control systems, there will be a radiator combined with a water-filled fusible heat sink. The three technological sources are servo-arduino motors, electric batteries, and x-band waves to facilitate navigation of the mission. The design requirements present by AIAA have been met.

14 Acknowledgements

Embrace The Martian would like to thank Scott Mescudi, also known as Kid Cudi, for inspiration on the team's name and design name. The team would also like to acknowledge Kennesaw State University, AIAA, NASA, and SpaceX. The team would like to also thank Elon Musk for the inspiration from his work. The team would also like to thank and acknowledge Nune Papikyan for aiding in video editing in Adobe After Effects. Finally, the team would like to thank Dr. Adeel Khalid for intellectual and emotional support during the duration of the project.

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16 Appendices

Appendix A: Contributions

Table 19. Technical Contributions by chapter

Chapter	**Contributor**
Executive Summary	Alejandro, Kamyar, Andrew, Kyle
Chapter 1: Overview	Andrew, Kyle, Kamyar, Alejandro
Chapter 2: Flow Chart	Andrew, Kyle
Chapter 3: Trade Research	Kamyar, Andrew, Kyle, Alejandro
Chapter 4: Resources	Kyle, Andrew
Chapter 5: Design	Kyle, Alejandro, Andrew
Chapter 6: Propulsions	Kyle
Chapter 7: Sources of Technology	Andrew, Alejandro, Kamyar
Chapter 8: Orbital Mechanics Analysis and Trajectory	Kyle
Chapter 9: Minimum Success Criteria	Kamyar, Andrew
Chapter 10: Schedule	Andrew
Chapter 11: Budget	Andrew, Kamyar
Chapter 12: Results	Andrew, Kamyar
Chapter 13: Conclusion	Kamyar, Andrew
Chapter 14: Acknowledgements	Kamyar
Chapter 15: References	Andrew, Kyle, Kamyar, Alejandro
Appendices	Andrew, Kyle, Kamyar, Alejandro

Table 20. Technical Contributions

Kamyar Karimian	Kamyar's primary contributions include trade research analysis, assisting in developing project requirements, budget assistance, team management, and documentation.
Kyle Mello	Kyle's primary contributions were the weight analysis, the orbital mechanics section and analysis, creating the mission profile, making the mission profile animation, and creating the CAD model for the rocket powered sky crane.
Alejandro Morales	Alejandro's primary contributions would be performing weight calculations, creating the rover CAD model, and researching new technology.
Andrew Nguyen	Andrew's primary contributions were budget research, assisting in weight calculations, managing the documentation of the project, and keeping the Gantt chart up to date.

Table 21. Bi-Elliptic Calculations from Phobos to Deimos

9376000	4.28E+13	25463200	17419600	23463200	24463200	446.755	318.65	27.34	792.7363	92984.94	1.076215
9376000	4.28E+13	26463200	17919600	23463200	24963200	459.993	313.14	40.00	813.1327	96288.16	1.114446
9376000	4.28E+13	27463200	18419600	23463200	25463200	472.453	307.79	52.06	832.2942	99630.66	1.153133
9376000	4.28E+13	28463200	18919600	23463200	25963200	484.2	302.58	63.55	850.3299	103012	1.192268
9376000	4.28E+13	29463200	19419600	23463200	26463200	495.293	297.52	74.53	867.336	106431.6	1.231848
9376000	4.28E+13	30463200	19919600	23463200	26963200	505.786	292.60	85.01	883.3983	109889.2	1.271866
9376000	4.28E+13	31463200	20419600	23463200	27463200	515.727	287.82	95.05	898.5932	113384.3	1.312319
9376000	4.28E+13	32463200	20919600	23463200	27963200	525.158	283.17	104.66	912.9891	116916.5	1.3532
9376000	4.28E+13	33463200	21419600	23463200	28463200	534.118	278.66	113.87	926.6474	120485.4	1.394507
9376000	4.28E+13	34463200	21919600	23463200	28963200	542.641	274.27	122.71	939.6232	124090.6	1.436234
9376000	4.28E+13	35463200	22419600	23463200	29463200	550.759	270.01	131.20	951.9666	127731.8	1.478377
9376000	4.28E+13	36463200	22919600	23463200	29963200	558.5	265.87	139.36	963.7226	131408.5	1.520932
9376000	4.28E+13	37463200	23419600	23463200	30463200	565.889	261.84	147.21	974.9321	135120.5	1.563895
9376000	4.28E+13	38463200	23919600	23463200	30963200	572.951	257.92	154.76	985.6323	138867.4	1.607262
9376000	4.28E+13	39463200	24419600	23463200	31463200	579.706	254.11	162.05	995.8571	142648.9	1.651029
9376000	4.28E+13	40463200	24919600	23463200	31963200	586.174	250.40	169.07	1005.638	146464.7	1.695193
9376000	4.28E+13	41463200	25419600	23463200	32463200	592.373	246.79	175.84	1015.002	150314.4	1.73975
9376000	4.28E+13	42463200	25919600	23463200	32963200	598.32	243.28	182.38	1023.976	154197.7	1.784696
9376000	4.28E+13	43463200	26419600	23463200	33463200	604.03	239.86	188.69	1032.584	158114.5	1.830028
9376000	4.28E+13	44463200	26919600	23463200	33963200	609.517	236.53	194.80	1040.848	162064.2	1.875744
9376000	4.28E+13	45463200	27419600	23463200	34463200	614.793	233.29	200.71	1048.787	166046.8	1.921838
9376000	4.28E+13	46463200	27919600	23463200	34963200	619.87	230.13	206.42	1056.422	170061.9	1.968309
9376000	4.28E+13	47463200	28419600	23463200	35463200	624.76	227.05	211.96	1063.768	174109.3	2.015154
9376000	4.28E+13	48463200	28919600	23463200	35963200	629.473	224.05	217.32	1070.842	178188.6	2.062368
9376000	4.28E+13	49463200	29419600	23463200	36463200	634.017	221.12	222.52	1077.658	182299.7	2.109951
9376000	4.28E+13	50463200	29919600	23463200	36963200	638.403	218.27	227.56	1084.231	186442.3	2.157897
9376000	4.28E+13	51463200	30419600	23463200	37463200	642.638	215.49	232.45	1090.574	190616.2	2.206206
9376000	4.28E+13	52463200	30919600	23463200	37963200	646.73	212.77	237.20	1096.697	194821.1	2.254874
9376000	4.28E+13	53463200	31419600	23463200	38463200	650.686	210.12	241.81	1102.613	199056.8	2.303898
9376000	4.28E+13	54463200	31919600	23463200	38963200	654.513	207.53	246.28	1108.332	203323	2.353276
9376000	4.28E+13	55463200	32419600	23463200	39463200	658.217	205.01	250.64	1113.863	207619.6	2.403005
9376000	4.28E+13	56463200	32919600	23463200	39963200	661.803	202.54	254.87	1119.215	211946.4	2.453083
9376000	4.28E+13	57463200	33419600	23463200	40463200	665.278	200.13	258.99	1124.397	216303	2.503507
9376000	4.28E+13	58463200	33919600	23463200	40963200	668.647	197.78	263.00	1129.418	220689.4	2.554276
9376000	4.28E+13	59463200	34419600	23463200	41463200	671.913	195.47	266.90	1134.283	225105.3	2.605386
9376000	4.28E+13	60463200	34919600	23463200	41963200	675.082	193.22	270.70	1139.002	229550.6	2.656835
9376000	4.28E+13	61463200	35419600	23463200	42463200	678.159	191.02	274.40	1143.579	234024.9	2.708622
9376000	4.28E+13	62463200	35919600	23463200	42963200	681.147	188.87	278.00	1148.021	238528.2	2.760743
9376000	4.28E+13	63463200	36419600	23463200	43463200	684.049	186.77	281.52	1152.335	243060.3	2.813198
9376000	4.28E+13	64463200	36919600	23463200	43963200	686.87	184.71	284.95	1156.525	247620.9	2.865982
9376000	4.28E+13	65463200	37419600	23463200	44463200	689.613	182.69	288.29	1160.597	252209.9	2.919096
9376000	4.28E+13	66463200	37919600	23463200	44963200	692.281	180.72	291.56	1164.556	256827.1	2.972536
9376000	4.28E+13	67463200	38419600	23463200	45463200	694.877	178.79	294.74	1168.406	261472.4	3.0263
9376000	4.28E+13	68463200	38919600	23463200	45963200	697.405	176.89	297.85	1172.152	266145.5	3.080388
9376000	4.28E+13	69463200	39419600	23463200	46463200	699.866	175.04	300.89	1175.798	270846.3	3.134795
9376000	4.28E+13	70463200	39919600	23463200	46963200	702.263	173.23	303.86	1179.348	275574.7	3.189522
9376000	4.28E+13	71463200	40419600	23463200	47463200	704.599	171.45	306.76	1182.806	280330.4	3.244565
9376000	4.28E+13	72463200	40919600	23463200	47963200	706.876	169.71	309.59	1186.175	285113.4	3.299924
9376000	4.28E+13	73463200	41419600	23463200	48463200	709.096	168.00	312.36	1189.458	289923.5	3.355595
9376000	4.28E+13	74463200	41919600	23463200	48963200	711.262	166.32	315.07	1192.66	294760.4	3.411579
9376000	4.28E+13	75463200	42419600	23463200	49463200	713.375	164.68	317.73	1195.782	299624.1	3.467872
9376000	4.28E+13	76463200	42919600	23463200	49963200	715.437	163.07	320.32	1198.828	304514.5	3.524473
9376000	4.28E+13	77463200	43419600	23463200	50463200	717.45	161.49	322.86	1201.8	309431.3	3.581381
9376000	4.28E+13	78463200	43919600	23463200	50963200	719.417	159.94	325.34	1204.702	314374.4	3.638593
9376000	4.28E+13	79463200	44419600	23463200	51463200	721.337	158.42	327.78	1207.535	319343.8	3.696108
9376000	4.28E+13	80463200	44919600	23463200	51963200	723.214	156.93	330.16	1210.302	324339.2	3.753925
9376000	4.28E+13	81463200	45419600	23463200	52463200	725.048	155.46	332.50	1213.006	329360.5	3.812042
9376000	4.28E+13	82463200	45919600	23463200	52963200	726.841	154.02	334.78	1215.648	334407.5	3.870458
9376000	4.28E+13	83463200	46419600	23463200	53463200	728.594	152.61	337.02	1218.23	339480.3	3.92917
9376000	4.28E+13	84463200	46919600	23463200	53963200	730.309	151.22	339.22	1220.755	344578.5	3.988177
9376000	4.28E+13	85463200	47419600	23463200	54463200	731.987	149.86	341.38	1223.225	349702.2	4.047479
9376000	4.28E+13	86463200	47919600	23463200	54963200	733.628	148.52	343.49	1225.641	354851.1	4.107073
9376000	4.28E+13	87463200	48419600	23463200	55463200	735.235	147.21	345.56	1228.004	360025.2	4.166958
9376000	4.28E+13	88463200	48919600	23463200	55963200	736.809	145.92	347.59	1230.318	365224.2	4.227133
9376000	4.28E+13	89463200	49419600	23463200	56463200	738.349	144.65	349.58	1232.582	370448.2	4.287595
9376000	4.28E+13	90463200	49919600	23463200	56963200	739.858	143.40	351.54	1234.799	375697	4.348345
9376000	4.28E+13	91463200	50419600	23463200	57463200	741.336	142.17	353.46	1236.971	380970.4	4.40938
9376000	4.28E+13	92463200	50919600	23463200	57963200	742.785	140.97	355.35	1239.098	386268.4	4.470699
9376000	4.28E+13	93463200	51419600	23463200	58463200	744.204	139.78	357.20	1241.182	391590.8	4.532301
9376000	4.28E+13	94463200	51919600	23463200	58963200	745.596	138.61	359.01	1243.225	396937.6	4.594185
9376000	4.28E+13	95463200	52419600	23463200	59463200	746.96	137.47	360.80	1245.226	402308.5	4.656349
9376000	4.28E+13	96463200	52919600	23463200	59963200	748.298	136.34	362.55	1247.189	407703.6	4.718792
9376000	4.28E+13	97463200	53419600	23463200	60463200	749.61	135.23	364.27	1249.113	413122.7	4.781512
9376000	4.28E+13	98463200	53919600	23463200	60963200	750.898	134.14	365.97	1251.001	418565.6	4.844509

Deimos to Parking Orbit											
r1 (m)	μ (m^3/s^	rb (m)Inde	a1 (m)	r2 (m)	a2 (m)	1st V (m/s	2nd V (m/	3rd V (m/s	Total V (m	TOF (s)	TOF (days)
23463200	4.28E+13	59790345	41626772.5	59790345	59790345	2.68E+02	210.94	0.00	479.0862	350864.3	4.060929
23463200	4.28E+13	60000000	41731600	59790345	59895173	2.69E+02	210.62	0.74	480.313	351935.5	4.073328
23463200	4.28E+13	61000000	42231600	59790345	60395173	2.73E+02	209.15	4.23	486.0701	357060.5	4.132645
23463200	4.28E+13	62000000	42731600	59790345	60895173	2.76E+02	207.69	7.64	491.6754	362210.9	4.192256
23463200	4.28E+13	63000000	43231600	59790345	61395173	2.80E+02	206.24	10.99	497.1348	367386.6	4.25216
23463200	4.28E+13	64000000	43731600	59790345	61895173	2.83E+02	204.81	14.27	502.4539	372587.5	4.312356
23463200	4.28E+13	65000000	44231600	59790345	62395173	2.87E+02	203.40	17.49	507.638	377813.5	4.372841
23463200	4.28E+13	66000000	44731600	59790345	62895173	2.90E+02	202.00	20.64	512.6924	383064.3	4.433615
23463200	4.28E+13	67000000	45231600	59790345	63395173	2.93E+02	200.62	23.73	517.6217	388340	4.494676
23463200	4.28E+13	68000000	45731600	59790345	63895173	2.96E+02	199.25	26.76	522.4305	393640.4	4.556023
23463200	4.28E+13	69000000	46231600	59790345	64395173	2.99E+02	197.89	29.74	527.1233	398965.3	4.617654
23463200	4.28E+13	70000000	46731600	59790345	64895173	3.02E+02	196.55	32.66	531.7041	404314.7	4.679568
23463200	4.28E+13	71000000	47231600	59790345	65395173	3.05E+02	195.23	35.52	536.1769	409688.4	4.741764
23463200	4.28E+13	72000000	47731600	59790345	65895173	3.08E+02	193.92	38.34	540.5455	415086.4	4.804241
23463200	4.28E+13	73000000	48231600	59790345	66395173	3.11E+02	192.63	41.10	544.8135	420508.5	4.866996
23463200	4.28E+13	74000000	48731600	59790345	66895173	3.14E+02	191.35	43.81	548.9844	425954.5	4.930029
23463200	4.28E+13	75000000	49231600	59790345	67395173	3.17E+02	190.08	46.47	553.0613	431424.5	4.993339
23463200	4.28E+13	76000000	49731600	59790345	67895173	3.19E+02	188.83	49.09	557.0475	436918.3	5.056925
23463200	4.28E+13	77000000	50231600	59790345	68395173	3.22E+02	187.59	51.66	560.9459	442435.8	5.120784
23463200	4.28E+13	78000000	50731600	59790345	68895173	3.24E+02	186.37	54.19	564.7594	447976.8	5.184917
23463200	4.28E+13	79000000	51231600	59790345	69395173	3.27E+02	185.16	56.67	568.4907	453541.3	5.249321
23463200	4.28E+13	80000000	51731600	59790345	69895173	3.29E+02	183.96	59.11	572.1425	459129.2	5.313996
23463200	4.28E+13	81000000	52231600	59790345	70395173	3.31E+02	182.78	61.51	575.7173	464740.4	5.37894
23463200	4.28E+13	82000000	52731600	59790345	70895173	3.34E+02	181.61	63.87	579.2175	470374.8	5.444153
23463200	4.28E+13	83000000	53231600	59790345	71395173	3.36E+02	180.46	66.20	582.6454	476032.2	5.509632
23463200	4.28E+13	84000000	53731600	59790345	71895173	3.38E+02	179.32	68.48	586.0032	481712.7	5.575378
23463200	4.28E+13	85000000	54231600	59790345	72395173	3.40E+02	178.19	70.72	589.293	487416	5.641389
23463200	4.28E+13	86000000	54731600	59790345	72895173	3.43E+02	177.07	72.93	592.5169	493142.1	5.707664
23463200	4.28E+13	87000000	55231600	59790345	73395173	3.45E+02	175.96	75.11	595.6769	498891	5.774201
23463200	4.28E+13	88000000	55731600	59790345	73895173	3.47E+02	174.87	77.25	598.7747	504662.5	5.841001
23463200	4.28E+13	89000000	56231600	59790345	74395173	3.49E+02	173.79	79.36	601.8123	510456.5	5.908061
23463200	4.28E+13	90000000	56731600	59790345	74895173	3.51E+02	172.72	81.43	604.7914	516272.9	5.975381
23463200	4.28E+13	91000000	57231600	59790345	75395173	3.53E+02	171.67	83.47	607.7136	522111.7	6.042959
23463200	4.28E+13	92000000	57731600	59790345	75895173	3.54E+02	170.62	85.48	610.5806	527972.7	6.110795
23463200	4.28E+13	93000000	58231600	59790345	76395173	3.56E+02	169.59	87.46	613.3939	533855.9	6.178888
23463200	4.28E+13	94000000	58731600	59790345	76895173	3.58E+02	168.57	89.41	616.155	539761.3	6.247237
23463200	4.28E+13	95000000	59231600	59790345	77395173	3.60E+02	167.56	91.33	618.8653	545688.6	6.31584
23463200	4.28E+13	96000000	59731600	59790345	77895173	3.62E+02	166.56	93.22	621.5262	551637.8	6.384697
23463200	4.28E+13	97000000	60231600	59790345	78395173	3.63E+02	165.57	95.09	624.1391	557608.9	6.453807
23463200	4.28E+13	98000000	60731600	59790345	78895173	3.65E+02	164.59	96.92	626.7052	563601.8	6.523169
23463200	4.28E+13	99000000	61231600	59790345	79395173	3.67E+02	163.63	98.73	629.2258	569616.3	6.592782
23463200	4.28E+13	1E+08	61731600	59790345	79895173	3.69E+02	162.67	100.52	631.7021	575652.5	6.662644
23463200	4.28E+13	1.01E+08	62231600	59790345	80395173	3.70E+02	161.73	102.28	634.1353	581710.2	6.732756
23463200	4.28E+13	1.02E+08	62731600	59790345	80895173	3.72E+02	160.79	104.01	636.5264	587789.3	6.803117
23463200	4.28E+13	1.03E+08	63231600	59790345	81395173	3.73E+02	159.86	105.72	638.8765	593889.8	6.873724
23463200	4.28E+13	1.04E+08	63731600	59790345	81895173	3.75E+02	158.95	107.41	641.1868	600011.6	6.944578
23463200	4.28E+13	1.05E+08	64231600	59790345	82395173	3.76E+02	158.04	109.07	643.4581	606154.6	7.015678
23463200	4.28E+13	1.06E+08	64731600	59790345	82895173	3.78E+02	157.15	110.71	645.6915	612318.7	7.087022
23463200	4.28E+13	1.07E+08	65231600	59790345	83395173	3.79E+02	156.26	112.33	647.8878	618504	7.158611
23463200	4.28E+13	1.08E+08	65731600	59790345	83895173	3.81E+02	155.38	113.92	650.0481	624710.2	7.230442
23463200	4.28E+13	1.09E+08	66231600	59790345	84395173	3.82E+02	154.52	115.49	652.1732	630937.4	7.302516
23463200	4.28E+13	1.1E+08	66731600	59790345	84895173	3.84E+02	153.66	117.05	654.2639	637185.4	7.374831
23463200	4.28E+13	1.11E+08	67231600	59790345	85395173	3.85E+02	152.81	118.58	656.3211	643454.2	7.447387
23463200	4.28E+13	1.12E+08	67731600	59790345	85895173	3.86E+02	151.97	120.09	658.3456	649743.7	7.520182
23463200	4.28E+13	1.13E+08	68231600	59790345	86395173	3.88E+02	151.13	121.58	660.3381	656053.9	7.593216
23463200	4.28E+13	1.14E+08	68731600	59790345	86895173	3.89E+02	150.31	123.05	662.2995	662384.6	7.666489
23463200	4.28E+13	1.15E+08	69231600	59790345	87395173	3.90E+02	149.49	124.51	664.2303	668735.9	7.739999
23463200	4.28E+13	1.16E+08	69731600	59790345	87895173	3.92E+02	148.69	125.94	666.1313	675107.6	7.813746
23463200	4.28E+13	1.17E+08	70231600	59790345	88395173	3.93E+02	147.89	127.36	668.0033	681499.7	7.887728
23463200	4.28E+13	1.18E+08	70731600	59790345	88895173	3.94E+02	147.10	128.76	669.8468	687912.1	7.961946
23463200	4.28E+13	1.19E+08	71231600	59790345	89395173	3.95E+02	146.32	130.14	671.6626	694344.8	8.036398
23463200	4.28E+13	1.2E+08	71731600	59790345	89895173	3.96E+02	145.54	131.50	673.4512	700797.6	8.111084
23463200	4.28E+13	1.21E+08	72231600	59790345	90395173	3.98E+02	144.78	132.85	675.2132	707270.6	8.186002
23463200	4.28E+13	1.22E+08	72731600	59790345	90895173	3.99E+02	144.02	134.18	676.9492	713763.6	8.261153
23463200	4.28E+13	1.23E+08	73231600	59790345	91395173	4.00E+02	143.26	135.49	678.6599	720276.6	8.336535
23463200	4.28E+13	1.24E+08	73731600	59790345	91895173	4.01E+02	142.52	136.79	680.3456	726809.6	8.412148
23463200	4.28E+13	1.25E+08	74231600	59790345	92395173	4.02E+02	141.78	138.07	682.0071	733362.4	8.48799
23463200	4.28E+13	1.26E+08	74731600	59790345	92895173	4.03E+02	141.05	139.34	683.6448	739935	8.564063
23463200	4.28E+13	1.27E+08	75231600	59790345	93395173	4.04E+02	140.33	140.59	685.2592	746527.4	8.640363
23463200	4.28E+13	1.28E+08	75731600	59790345	93895173	4.05E+02	139.62	141.82	686.8507	753139.5	8.716892
23463200	4.28E+13	1.29E+08	76231600	59790345	94395173	4.06E+02	138.91	143.05	688.42	759771.2	8.793648
23463200	4.28E+13	1.3E+08	76731600	59790345	94895173	4.08E+02	138.21	144.25	689.9674	766422.4	8.87063
23463200	4.28E+13	1.31E+08	77231600	59790345	95395173	4.09E+02	137.51	145.45	691.4935	773093.2	8.947838
23463200	4.28E+13	1.32E+08	77731600	59790345	95895173	4.10E+02	136.83	146.63	692.9985	779783.5	9.025272
23463200	4.28E+13	1.33E+08	78231600	59790345	96395173	4.11E+02	136.15	147.79	694.4831	786493.1	9.10293
23463200	4.28E+13	1.34E+08	78731600	59790345	96895173	4.12E+02	135.47	148.94	695.9475	793222.1	9.180812

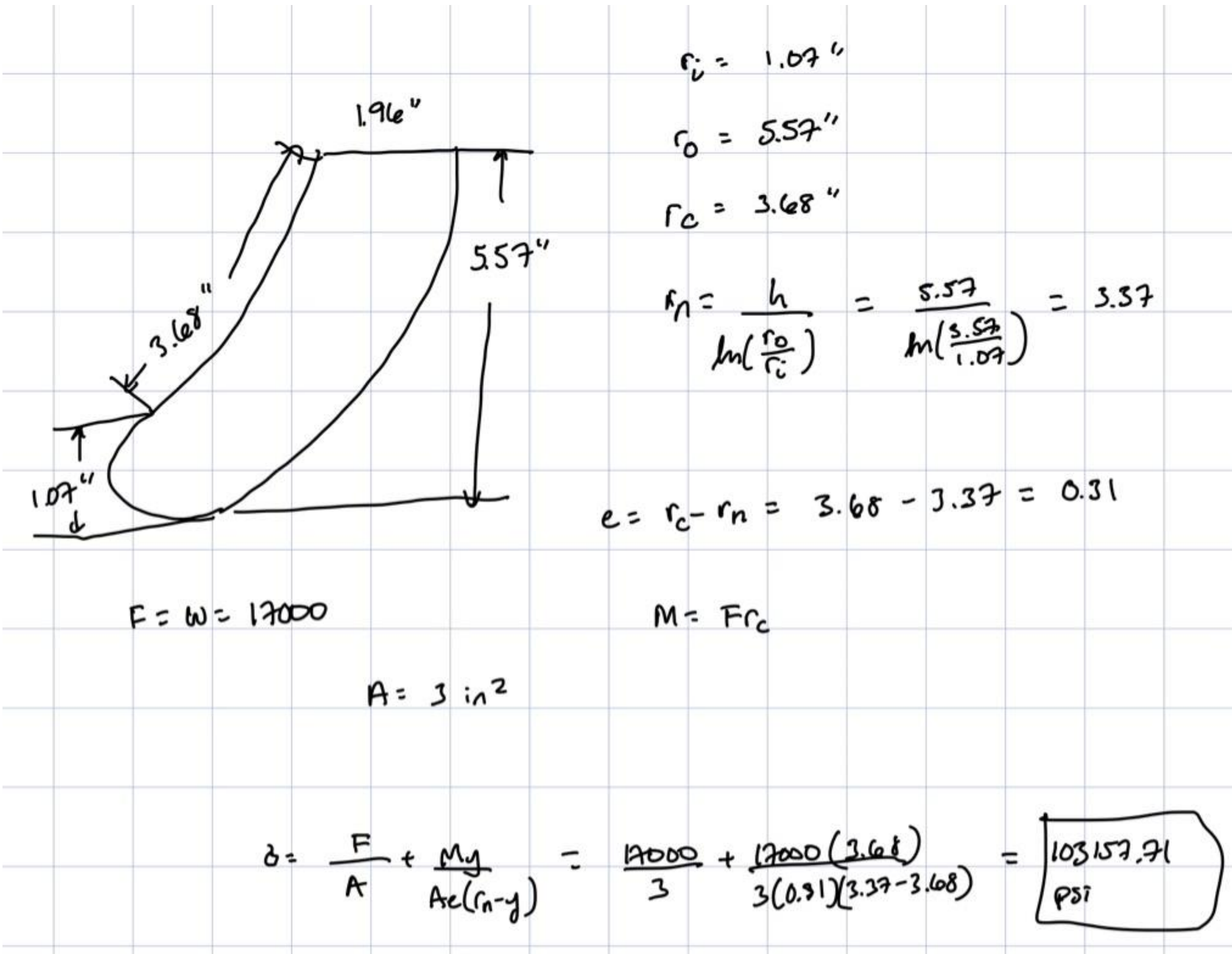

Figure 28. Hook Stress Hand Calculations

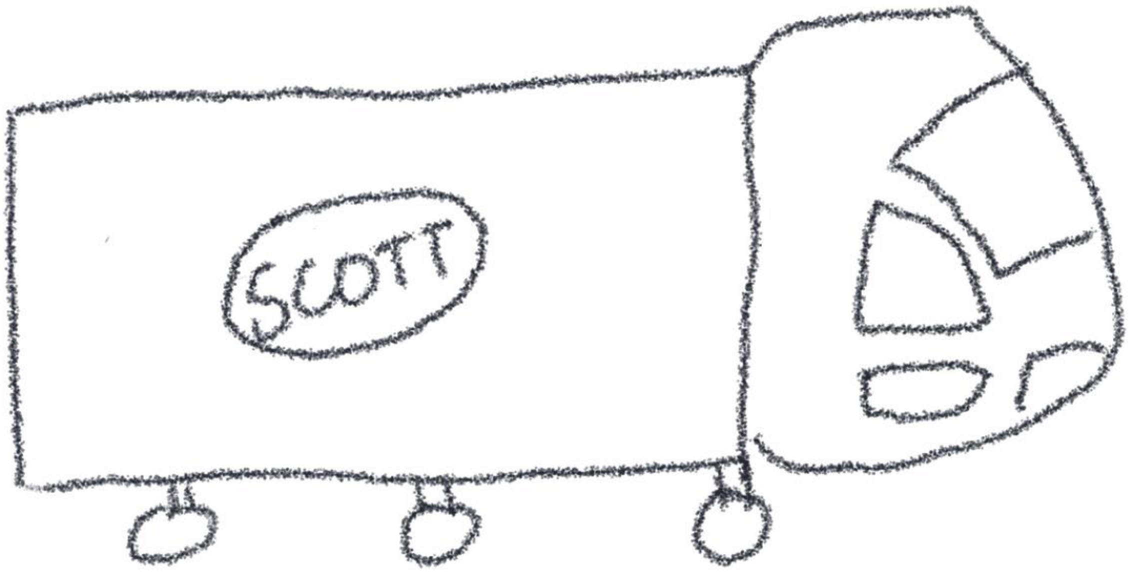

Figure 29. Hand Sketch drawn by Andrew Nguyen

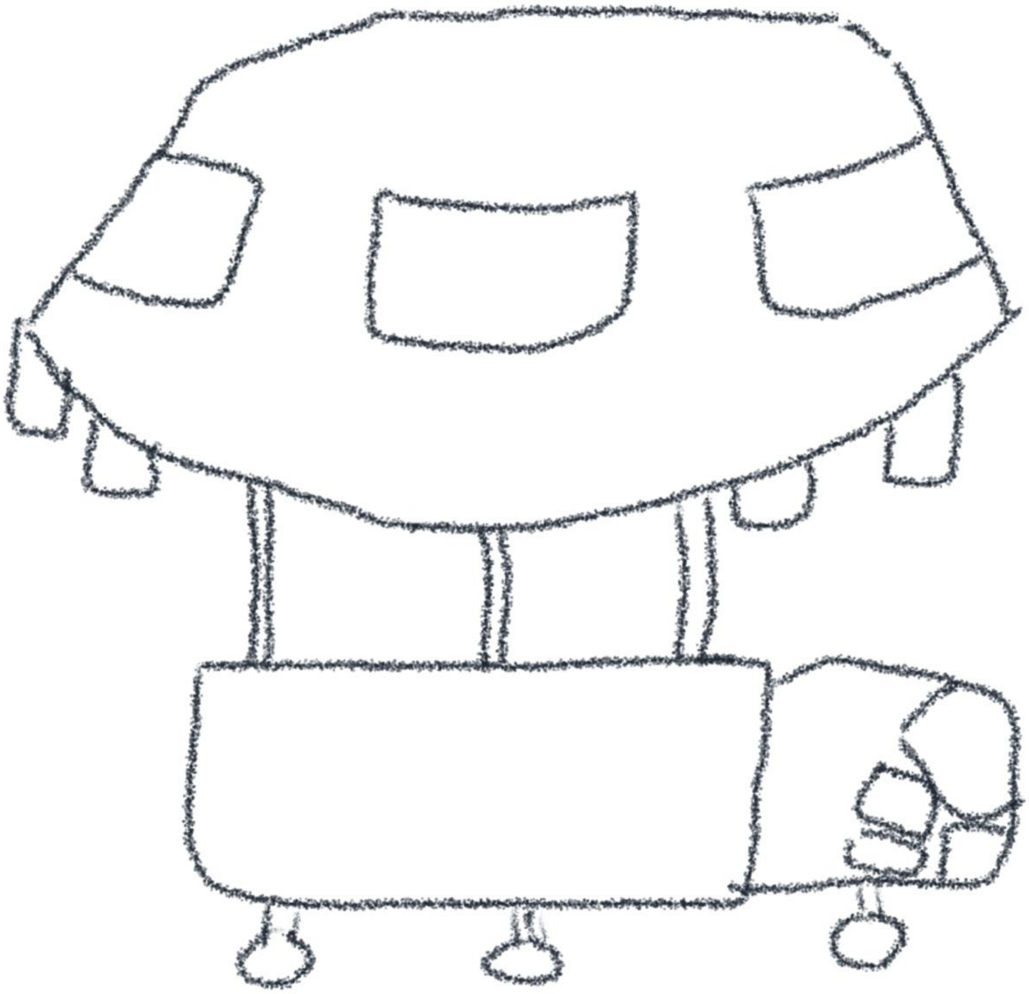

Figure 30. Initial sketch of sky crane component of SCOTT

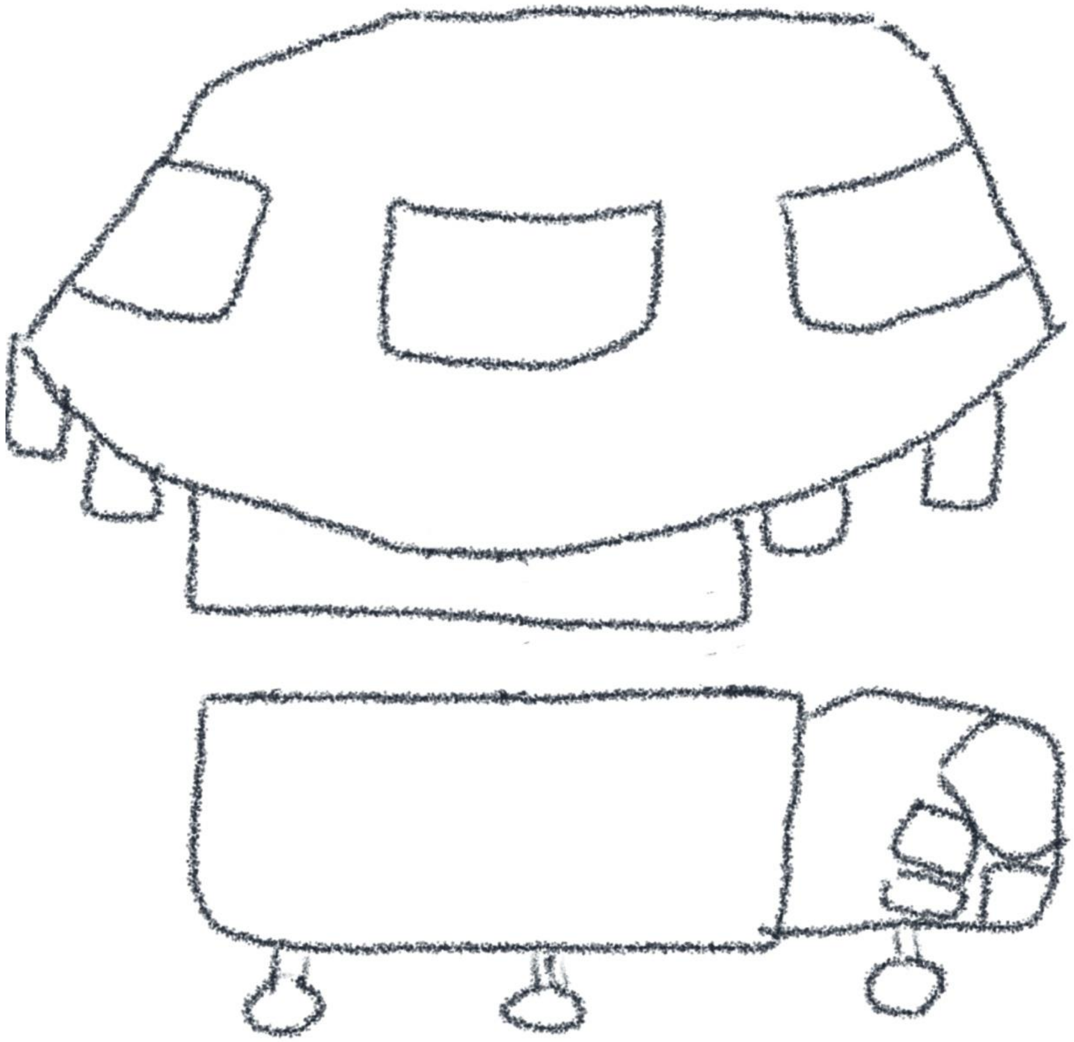

Figure 31. Initial sketch of sky crane, ramp approach