Project Aurora: Cubesat Launch System

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Abstract: The bleak and barren wastelands of the apocalypse thought only to exist in Hollywood have somehow materialized in the real world. Contrary to all expectations, zombies have taken over our society with next to no warning. Yet another miracle? West Lafayette somehow still stands.

The community in West Lafayette has decided to take this opportunity to fight back for the human race. With the resources it still has, the survivors here think it is possible to enact aerial search-and-rescue missions. Unfortunately for them, all ability to use satellites or GPS have already been knocked out, and hordes of roaming zombies prevent traditional scouting missions. On the bright side, the resources here in West Lafayette, combined with the engineering ability of our teams, provide the perfect solution.

For our contribution to the salvation of humanity, we have designed a system to locate pockets of survivors stranded around the world. To best accomplish this, we designed a 2-stage rocket that could carry 3 cubesats to an orbital altitude of 500 km. These cubesats were designed to find human survivors using thermal imaging technology. We decided on these parameters using a risk matrix, assessing different aspects of the design that we determined to be the most likely to fail. Through this risk analysis, we gained insight regarding how we could better design our system. We created 3 different concept models to complete the mission and then considered

the pros and cons of each to narrow down to our final design. Once we determined our final design, we modeled and perfected it.

Ultimately, our three-cubesat launch mission is backed up by historically successful technologies (such as common fuels), has few failure points due to low complexity, and is feasible in light of current limitations. Further, the mission fulfills all necessary requirements, ensuring that proper data will be collected for the sake of survivors everywhere. While we have found that the limited resources do impact the effectiveness of the mission, we believe our design is optimal given the extreme circumstances. Project Aurora: Cubesat Launch System, upon successful completion of its mission, will make its mark on human history by conserving human life itself.

9. Make it pretty

10. Proper page number in table of contents

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1 Introduction

This report describes the scenario of the zombie apocalypse, introduces the team's solution to the scenario, provides the mission statement and requirements for the project, and explains, in-depth, the different aspects of the design process and solution. This report also discusses the different stakeholders affected by the project, along with the needs and requirements set forth that guide the design. After the needs and requirements, there is a preliminary risk analysis that the team used to assess how likely different failures would be and the consequences resulting from them. The team's concept generation and development follows the risk analysis section and describes three different ideas that were envisioned to achieve the project's requirements. The best idea was selected based on how well it met these requirements and if it seemed the most feasible. This idea was then expanded on to provide more detailed information regarding how it actually would work and succeed if built. Finally, the conclusion of the report is where a summary of the project details can be found.

Ultimately, our mission is to create a fuel-efficient, technologically feasible, and reliable system, sturdy enough to endure the stresses of launch, which will deliver cubesats into distinct orbits and maximize the amount of apocalypse survivors that can be located for future rescue operations.

2 Needs and Requirements Analysis

In this section, the stakeholders, a list of the different people affected by the mission's success, are listed. Furthermore, this section studies the needs and requirements of the mission, as they are the base for success in the mission. The relationship between various needs and requirements is also demonstrated. Finally, this section covers the potential risks that the mission might face, as well as providing possible mitigations for these risks.

2.1 Stakeholders

The project should be designed with respect to the stakeholders. Although they do not explicitly define the needs, it was assumed that the needs were developed from the ground up as a result of the relevant stakeholders. Seeing as they are the individuals that are concerned with the success of the project, it is important to keep in mind their needs and circumstances.

With that said, stakeholders were determined by the assessment of groups related to the issues the project addresses. Any group who was affected by either the failure or success of the project's mission was considered a stakeholder.

The team's stakeholders are as follows:

- **The survivors in West Lafayette**: They want a system to send cubesats into space to search for survivors. In order for this to be completed, a successful launch of the cubesats is required.
- **Any survivors outside of West Lafayette:** Survivors outside of the community will depend on the success of the mission to be found and rescued. If they are properly located, they have a higher chance of being picked up.
- **The zombies:** The zombies around the world will be negatively affected by the success of this mission. If more survivors are found, then the zombies will have less people from which they can feed off of and they will starve.
- **Project development teams:** This team and others are dependent on the success of this system, as any team who doesn't have a winning design will be sent out as a scouting

team. As such, in the event of creating a poor project, a team will likely have their fate sealed.

2.2 Needs

The needs for the project were selected by identifying the factors that would lead to a successful mission. The most important need for the cubesat is that it sends data back to Earth and the most important need for the rocket is that it delivers the appropriate cubesats into a desired orbit. These needs are an absolute must for success.

As it stands, this project will not incorporate the design of the cubesats themselves. Rather, the cubesat are assumed to meet certain criteria. See the Cubesat Assumptions for further specifications regarding the cubesats.

Cubesat Needs:

1. The cubesat has thermal imaging.
2. The satellite sends thermal images back to Earth. This will help determine if a thermal source is coming from a living being or from a static source.
3. The thermal imaging on the cubesat has the ability to differentiate between people and other stray thermal energy (which could come from sources such as heating systems, animals, etc.).
4. The cubesat can operate in orbit long enough for the majority of survivors within aircraft range to be found.
5. The cubesat optimizes the amount of data it stores from imaging by reducing the amount of irrelevant pictures taken. This reduces the amount of data the cubesat stores.
6. The cubesat remains operational during crucial parts of the mission.

Rocket Needs:

1. The rocket is able to send a desired number of cubesats into a proper orbit.
2. Rocket materials can withstand heat of launch and exiting the atmosphere

3. The rocket is equipped with attitude control to maintain stability on launch and to guide it to the correct orbit.
4. The rocket is able to launch multiple cubesats into different orbits.
5. Rocket (including fuel and structures) can be built using the materials readily available at Purdue and the greater Lafayette area.

2.3 Rocket Requirements and Cubesat Assumptions

This team defined the mission requirements according to the needs for each individual component of the rocket and cubesat. It was determined that the most important requirement is that the rocket reach its target altitude/orbit. If the altitude attained is significantly lower the target altitude, the mission will be considered a failure. Furthermore, the cubesat must be able to communicate data and thermal imaging back to ground in order for it to be analyzed by professionals.

Cubesat Assumptions:

1. The cubesat camera has a sufficiently high resolution at a 500 km orbit to allow team members or professionals to differentiate between a group of people and other objects giving off heat. The altitude of 500 km is optimal for the camera to operate and will be the altitude of the cubesats.
2. The cubesat has software that is capable of differentiating between humans from other objects.
3. The cubesat has software that takes pictures only when thermal objects are detected.
4. The cubesat has a large enough battery to allow it to transmit data and operate on the dark side of Earth, while also allowing it to generate power for the entire duration of the mission.

Rocket Requirements:

1. The rocket has an alloted payload space sufficient to fit 3 different 10cm x 10cm 3U cubesats. Having three cubesats will allow for more regions of the earth to be explored.

2. The rocket is able to place at least a 50 kg payload into orbit, which is equivalent to the total mass of the 3 cubesats.
3. The rocket is designed with a payload distribution system that allows for satellites to be launched in different directions, as a single cubesat would not efficiently cover enough ground to rescue survivors.
4. The rocket inserts the cubesat into an orbit with an altitude of around 500 km. If launched to a higher orbit, the resolution of images suffers and it covers fewer regions in more time due to its larger period (Clark, 2015).
5. The rocket materials can withstand atmospheric temperature conditions, as rocket launches produce much less heat than re-entry (Scharringhausen, 2015). The chamber should be able to withstand exhaust heats (an estimated 3000K).
6. The rocket has a control system that will adjust its attitude while in flight in to maintain steady flight.
7. The design is optimized with considerations of fuel and weight efficiency. In particular, any design complication that can be reasonably avoided while maintaining mission success will be cut out, to simulate the limited resources at Purdue.

Cubesat Needs & Assumptions

Table 1: Cubesat Needs and Assumptions - Each cubesat need is matched with its respective assumption to satisfy it.

Needs:	**Assumptions:**
1.The cubesat has thermal imaging.	1. The cubesat camera has a sufficiently high resolution at a 500 km orbit in order to allow team members to differentiate between a group of people and other objects giving off heat. The altitude of 500 km is optimal for the camera to operate and will be the altitude of the cubesats.
2. The satellite communicates images back to Earth.	
3. The thermal imaging on the cubesat has the ability to differentiate between people and other stray thermal energy.	2. The cubesat has software that is capable of differentiating between humans from other objects.
4. The cubesat can operate in orbit for the duration of the mission.	3.The cubesat has software that takes pictures only when thermal objects are detected.
5. The cubesat optimizes the amount of data it stores from imaging by reducing the amount of irrelevant pictures taken. This reduces the amount of data the cubesat stores.	4. The cubesat has a large enough battery to allow it to transmit data and operate on the dark side of Earth, while also allowing it to generate power for the entire duration of the mission.

6. The cubesat remains operational during crucial parts of the mission.	

Table 2: Rocket Needs & Requirements - Each rocket need is matched with its respective requirement to satisfy it.

Needs:	**Requirements:**
1. The rocket is able to send a desired number of cubesats into a proper orbit.	1. The rocket has an alloted payload space sufficient to fit 3 different 10cm x 10cm 3U cubesats. Having three cubesats will allow for more regions of the earth to be explored.
	2. The rocket is able to place at least a 50 kg payload into orbit, which is equivalent to the total mass of the 3 cubesats.
	4. The rocket inserts the cubesat into an orbit with an altitude of around 500 km. If launched to a higher orbit, the resolution of images suffers and it covers less regions in more time due to its larger period (Clark, 2015). (See Development of Concept 2, Section a, ii for further analysis.)

2. Rocket materials can withstand heat of launch and exiting the atmosphere	5. The rocket materials can withstand atmospheric temperature conditions, as rocket launches produce much less heat than re-entry(Scharringhausen, 2015). The chamber should be able to withstand exhaust heats (estimating 3000K).
3. The rocket is equipped with attitude control to maintain stability on launch and to guide it to the correct orbit.	6. The rocket has a control system that will adjust its attitude while in flight in to maintain steady flight.
5. Rocket materials (including fuel and structures) can be built using materials readily available at Purdue.	7. The design is optimized with considerations of fuel and weight efficiency. In particular, any design complication that can be reasonably avoided while maintaining mission success will be cut out, to simulate the limit resources at Purdue.
4. The rocket is able to launch multiple cubesats into different orbits.	3. The rocket is designed with a payload distribution system that allows for satellites to be launched in different directions, as a single cubesat would not efficiently cover enough ground to rescue survivors.

2.4 Preliminary Risk Analysis

In order to ensure mission success and design around the failures that could occur, a risk analysis was done for the rocket. Using NASA's Risk Matrix (Figure 1), the probability of a failure and the consequences of a failure were both assessed. NASA has balanced these traits to show how probability and consequence work together to indicate the potential a certain risk has of creating a mission failure. The assessment of the system is shown below for various aspects of the design.

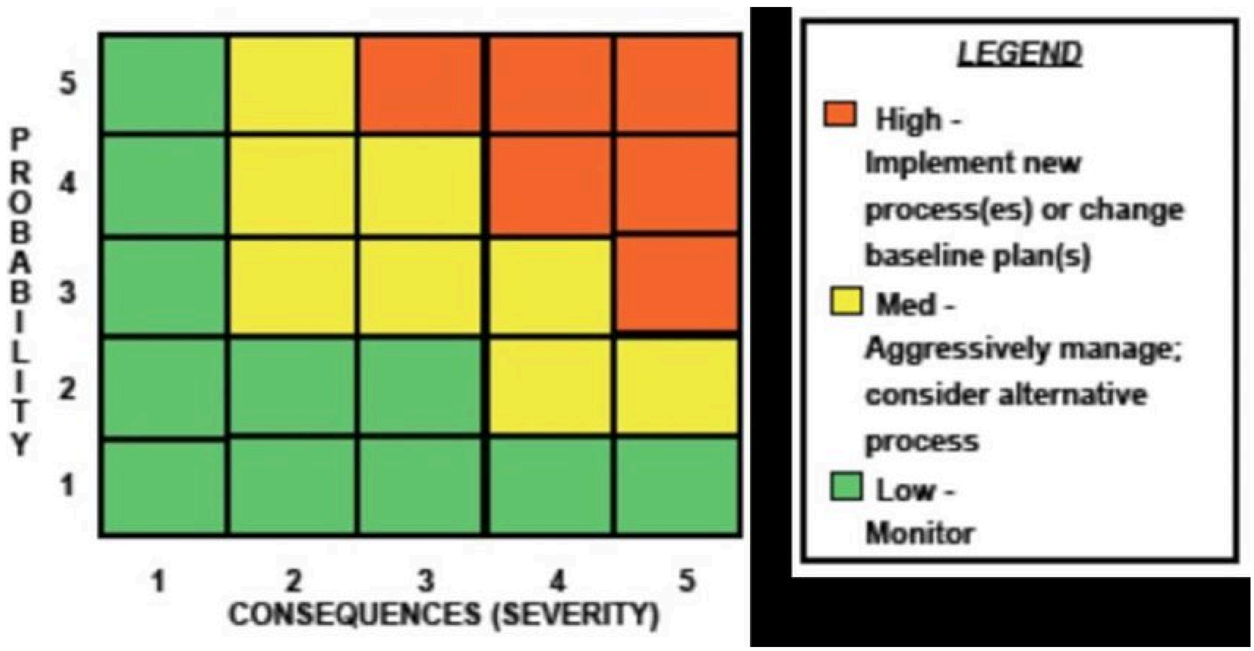


Figure 1: NASA Risk Matrix - The figure shows an example of NASA's mission risk matrix, which was used to assess the mission's risk severity.

First-stage Risk:

I. The rocket explodes
   A. The materials of the rocket are unable to withstand the high temperatures and stress of launch.

Possible mitigations: use of reliable/tested materials, structural analysis, simulations

B. Mechanical or electrical components of the rocket fail during launch.

Possible mitigations: redundant systems, test components prior to launch, pre-launch inspections

II. The rocket is unable to launch

A. Electrical systems shut down

Possible mitigations: redundant systems, test components prior to launch, pre-launch inspections

B. Harsh conditions inhibit launch

Possible mitigations: clear go/no-go conditions, delay launch time or day

III. The rocket goes off course

A. Inclement weather conditions

Possible mitigations: clear go/no-go conditions, delay launch

B. Guidance systems fail

Possible mitigations: redundant systems, component testing, pre-launch inspections

IV. Inconsistent thrust

A. Burning instability in fuel

Possible mitigations: quality control of fuel

Table 3: First-stage Risk Matrix - Evaluation of first-stage risks on NASA's risk matrix.

5					
4	II-B				
3		III-A			
2	II-A	III-B			I-A; I-B
1		IV-A			
^Probability Consequence >	1	2	3	4	5

The first stage risk seems mostly manageable, with none of them being assessed as "red." It is notable that catastrophic failure of the rocket is possible due to heat, stresses, or component failures. This is made more probable with the lack of broad and professional manufacturing options; because the apocalypse limits resources, the quality of the rocket may decrease. Nonetheless, the rocket should be able to launch properly with the resources provided.

Further, inconsistent thrust or guidance failure is possible, though unlikely and not completely detrimental. Finally, if prevented from launching altogether due to weather factors, it would only imply delaying launch and would not be considered be a serious issue.

Second-stage Risk:

I. The first stage separation goes wrong
    A. Bad separation due to uncoordinated explosions from explosive bolts

        Possible mitigations: component testing, pre-launch inspections

II. Second stage engine doesn't start

        Possible mitigations: attempted re-ignition of engine, component testing, pre-launch inspections

III. Inconsistent thrust from engine

A. Flame instability

Possible mitigations: quality control of fuel

B. Inconsistent fuel flow rate

Possible mitigations: component testing, pre-launch inspections

IV. Second stage goes off course

A. Ignition of second stage before decoupling causing rocket to go off course or catastrophic failure.

Possible mitigation: sensors that prevent second stage from firing if decoupling isn't detected.

Table 4: Second-stage Risk Matrix - Evaluation of second-stage risks on NASA's risk matrix.

5					
4					
3					
2		III-B			
1		III-A			I-A; II; IV-A
^Probability Consequence >	1	2	3	4	5

The second stage risk has also been found to be manageable, with everything falling under the "green" section. Failures such as improper separation, going off course, or the stage not firing could cause total mission failure, but with only two stages, it is believed that the complexity will be low enough to make these failures improbable.

Engine consistency may be more likely in this case, as it is a liquid engine and will require more precise controls as it orients the rocket in orbit. Nonetheless, this risk is manageable with proper testing.

Payload Risk:

I. Fairing doesn’t separate

Possible mitigations: pre-flight inspection, back up pyrotechnics

II. Each cubesat doesn’t deploy properly

A. Mis-timed release of payload

Possible mitigations: thorough ground testing of hardware, pre-flight inspection, wait one orbital period to release the cubesat

B. Mechanism failure

Possible mitigations: component testing, pre-launch inspections

III. Payload is damaged during boarding/launch

A. Mishandling of payload

Possible mitigations: proper handling procedures, designs that considers payload safety

B. Internal systems issues that spread to payload bay

Possible mitigations: separate payload system from the body of the rocket

Table 5: Payload Risk Matrix - Evaluation of payload risks on NASA's risk matrix.

5					
4					
3					
2			II-A		I; III-B
1			II-B; III-A		
^Probability Consequence >	1	2	3	4	5

The risks to the payload also fall within an acceptable range. Should the fairing not separate properly, then the mission cannot move forward, but, similarly to stage separation, this isn't likely. If something goes catastrophically wrong in the rest of the rocket, the payload may also be damaged, causing mission failure. With proper assessment of the other risks, this shouldn't occur.

Deployment failure is unlikely as well (after component testing), but may not be as impactful. If a cubesat is slightly off its orbit, the mission will still gather data, even if it is less optimal. Additionally, it is completely unlikely that the payload will be mishandled given the importance the community has placed on the mission.

Cubesat Risk:

I. Camera will not work

   A. Radiation/Charged Particles

      Possible mitigations: shielding, redundant systems, hardened components, radiators

   B. Fault in manufacturing

Possible mitigations: pre flight inspection /review

II. Solar panels will not work
   A. Radiation/Charged Particles

Possible mitigations: shielding, redundant systems, hardened components, radiators

III. Radio communication will not work
   A. Radiation/Charged Particles

Possible mitigations: shielding, redundant systems, hardened components, radiators

IV. Thermal Imaging doesn’t pick up proper heat signatures from people

Possible mitigations: pre flight inspection, backup hardware

V. Cubesat hits space debris

Possible mitigations: cautious launches/debris scans, multiple payloads to reduce risk of total failure, durable parts

VI. Solar pressure changes course of cubesat

Possible mitigations: control/account for added force

Table 6: Cubesat Risk Matrix - Evaluation of cubesat risks on NASA's risk matrix.

5					
4					
3					
2	I-B			IV	I-A; II-A; III-A
1		VI		V	
^Probability Consequence >	1	2	3	4	5

Finally, the cubesat risks also seem manageable, though perhaps the most concerning, considering the frailty of a cubesat and its inability to house propulsion systems to adjust or protect itself. Failures in the electronics are very possible in the space environment, but can be accounted for in redundant systems (where space is available) and redundant programs.

Debris, solar pressure, and manufacturing issues are mostly unlikely; debris is the most impactful of them. These hazards can mostly be avoided, though debris may require luck more than anything, due to the physical limitations of the cubesat. On the other hand, this mission launches multiple cubesat systems, so the failure of one can be mitigated by the others.

Finally, if the cubesats cannot properly pick up on people, the mission becomes less useful, but not a complete failure. It would still detect heat sources, which would give indications as to where people might be found. Regardless, proper testing of the devices should ensure that doesn't happen.

3 Concept Generation, Selection, and Development

In this section, the reader will find the process behind the concept generation, selection, and development for this project.

Three initial concepts were developed for the specific mission requirements the team established. Notably, Concept 2 was chosen as the optimal solution and developed further than the other concepts. As such, Concept 2 is elaborated on in section 3.2.

3.1 Concept Generation and Selection

Each concept was developed as a result of multiple brainstorming sessions whilst focusing on the mission requirements. Concepts were fleshed out or refined through criteria such as feasibility (given limited resources at Purdue), complexity or risk, and how effectively the design completed the mission. The following concepts are the results.

Concept 1:

General Description:

This concept centers around cost efficiency and simplicity. It entails a rocket launched with azimuth 0 from West Lafayette that carries a payload of a single cubesat. The rocket will have one stage. The cubesat is sent into a polar orbit around the Earth (inclination of 90 degrees). The rocket will launch to the desired altitude of 500 km, which optimizes the cubesats camera resolution to 81m^2 per pixel. Furthermore, the altitude of 500 km is a standard for most observation satellites (Clark 2015). Due to the mechanics of Earth's rotation (seeing as the Earth is rotating perpendicularly to the orbital inclination), the cubesat will eventually cover the entirety of Earth, giving access to all relevant information at the cost of a single cubesat and solely enough fuel to place it in the desired orbit. An rough visualization of this concept's mission is shown below.

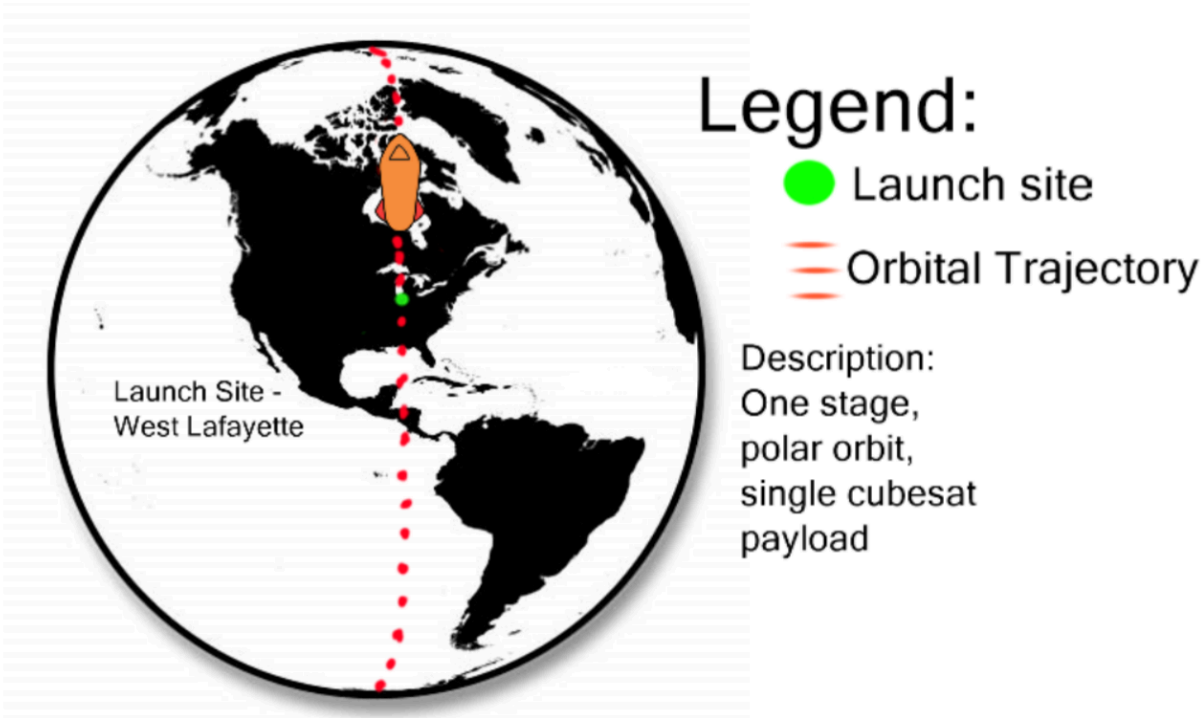


Figure 2: Concept 1 Diagram - A visual representation of Concept 1, including launch site and intended orbital trajectory.

Some of this concept's benefits are as follows:

This concept maximizes cost efficiency and simplicity while ensuring the completion of the mission. Due to this simplicity, it also avoids the possibility of colliding cubesats and the equations are simplified enough that relevant data can all be tracked and calculated (relatively) easily.

Moreover, the main launch is entirely devoted to ensuring the cubesat enters the correct orbit, so only enough fuel for that orbit is required. There are also no complex mechanisms needed to put cubesats into different orbits.

On the other hand, this concept entails major risks as well. The biggest is that only one cubesat will be launched aboard the rocket. This makes the mission fragile, as the entire success of the mission is dependent on a single cubesat. As such, any failure or malfunction in one cubesat would mean that the mission is a failure. At the same time, the time taken for mission completion will increase, as there will only be one cubesat taking photos. It should be noted that, while cost efficiency important, rescuing as many survivors as possible is more important.

Finally, a polar orbit would not gain any help from the earth's rotation, meaning that this concept requires a rocket that can produce the most ΔV necessary for its desired orbital altitude.

Development of concept 1:

This concept was initially suggested as a simple means of accomplishing the mission. After learning that a single cubesat could cover the entire planet regarding data collection (by means of a polar orbit), it seemed as though this could be a simple and cost efficient option. It would involve very few complexities regarding the rocket, such as mechanisms for launching into different orbits or having to use separate heights for multiple cubesats.

As the concept was fleshed out, some drawbacks became apparent. On one hand, the orbit does not utilize Earth’s rotational speed at all. While this is a drawback, all the fuel for the rocket is intended to achieve a polar orbit, so that likely isn’t the biggest issue.

On the other hand, the data collection period is the most troubling part of the concept. The process would take a significant amount of time. As shown in further in Section 3.2, each individual cubesat cannot cover a massive area with each picture. Even if the cubesat was always covering new parts of the Earth, much of the Earth is ocean, and it would take significant time to scan the entire planet. Of course, in reality, some data will be duplicated before all of the data is collected, so the situation is even worse.

Finally, relying on a single cubesat seemed risky in light of the potential space hazards that were being considered, such as malfunctions due to radiation or space debris. In light of the time-intensive mission, this compounds the risk that the cubesat goes down before the necessary or desired amount of data is collected, rendering the mission a failure.

With these considerations in mind, it was accepted that Concept 1 was too simple and needed to built up further in order to create a successful mission, leading to the development of Concept 2.

Concept 2:

General Description:

This concept will utilize a two stage rocket with a kickstage, and will be launched at an inclination of zero degrees. A kickstage is a mechanism produced by Rocket Lab which launches multiple payloads into different orbits (R, 2019). This design does not include the kickstage's individual propulsion system, but merely the spring mechanism that will launch the cubesat. This kickstage will house three 3U Cubesats: one cubesat achieving polar orbit, one cubesat at an inclination of 135°, and one cubesat achieving orbit at a 45° inclination; all of them will be orbiting at an altitude of 500 km. This will be achieved via the kickstage, which will act as a payload distribution system. The kickstage will launch multiple cubesats from the rocket (once the initial orbit is achieved) using springs to expel the cubesats into their respective inclinations. Regarding staging and engines, the rocket engine specifications are shown in Table 10; these specifications, along with others, are elaborated on in Section 3.2.

The general concept is illustrated below:

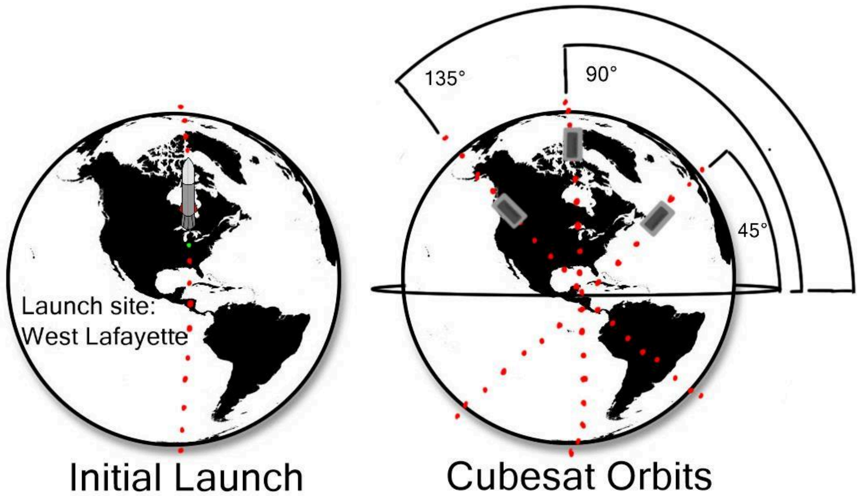


Figure 3: Concept 2 Diagram - A visual representation of Concept 2, which launches a 2 stage rocket on a polar orbit. It then launches three cubesats at the specified orientations.

Generally speaking, this concept distinguishes itself because it allows for multiple cubesats to be launched into orbit from a single launch. The kickstage mechanism launches payloads at multiple orbital inclinations once a circular orbit is reached (Pignatelli, n.d.). Launch of multiple cubesats hedges bets against the failure of a singular cubesat, as the other cubesats would still be sending data back to earth; this remedies a fatal flaw from Concept 1.

Another benefit is that the mission could be accomplished in less time due to the increased coverage from the three cubesats. As time is a key element in the search for survivors during the zombie apocalypse, this increases the chances of successfully locating survivors.

Finally, the staging allows for different engines and propellent types to be used for different purposes. As elaborated on in Section 3.2, solid and liquid engines are more useful in different situations, and this was used to better suit the design.

On the other hand, the system requires the complexity of stage separation, the kickstage, and multiple cubesats to achieve the mission, thus introducing more points of failures. While this risk is certainly manageable (after all, the complexity is far lower than what has been proven in industry), it still exists.

Furthermore, the cubesats aren't exceptional at covering area with their cameras, so even three of them may not collect as much data as is necessary for the mission. However, due to the limited materials of the mission, a full-size satellite cannot be used to remedy this situation, and the increasing complexity of adding more cubesats at the same altitude increases the chances of cubesat collision and of kickstage failure. As such, Concept 2 has some clear drawbacks, but is agreed to be the most reasonable and reliable solution.

The remainder of Concept 2 is elaborated on in Section 3.2, including detailed development notes, calculations, and specification tables.

Concept 3:

General Description:

The third idea developed is to launch a rocket from an unmanned aerial vehicle. The UAV would fly to the lower portion of the mesosphere and deploy the rocket. The UAV would pitch to an angle of attack equivalent to the rocket's trajectory and release the rocket to fire into space. Also, the UAV would be flying along a path equivalent to the azimuth of the rocket. This technique reduces the size of the rocket and the amount of propellant it has to carry. Also, by launching from a higher altitude, the amount of atmospheric drag the rocket encounters is significantly decreased.

Although this concept would provide benefits, the costs would be very high. To begin with, this concept increases in complexity and cost compared to the other two. Although the propellant needed for the rocket would decrease, the aircraft would require more propellant, as it is carrying a rocket. At the same time, this concept would necessitate the design and manufacturing of an additional airplane with the limited resources available in West Lafayette.

An increase in complexity also means an increase in the points of failure. This increase mostly comes from the UAV. The UAV would need to achieve max velocity while also maintaining stability. During the launch sequence, the UAV would need to fly at a high angle of attack, making it even harder to ensure a stable flight. Releasing a rocket from a UAV would also require multiple tests, as this method is still new and yet to be perfected with current technology. In the past, there have only been a handful of successful projects, and many more failures. For this design, seeing as it will be built with limited manufacturing resources, it was much more desirable to rely on historically proven techniques.

Of course, the benefit lies in the help provided from the UAV. The rocket will be less complicated, potentially even reducing the stages necessary to one stage . At the same time, the UAV would be reusable, allowing launches multiple times in a short window.

Development of concept 3:

Concept 3 initially came about in the discussion of staging rockets. As an alternative to staging, an aircraft to assist the rocket's launch would help eliminate weight of the rocket itself and would likely not have as many complications with staging. A large part of this idea was inspired by Virgin Galactic's SpaceshipTwo, which utilizes the WhiteKnightTwo as a carrier vehicle. SpaceshipTwo is already working with NASA to launch small payloads, and thus the purpose of the mission has been shown to be possible (Staff, 2018).

As concepts developed, it was understood that complexity become a large concern in mission success. The more complex an idea is, the more opportunity there is for it to fail. The launch of the rocket from an aircraft would require an entirely new system to be designed (though it could be based on SpaceShipTwo). Notably, as per requirement 7, the intended solution should seek to avoid heavy material use and complications. As such, adding an entirely separate system seems as though it could pose problems. The materials used for designing a carrying plane would be very specific and would be required in addition to those used on the rocket.

The novelty of the technology and how it can be successfully implemented make planning around these failure conditions more difficult, not to mention the challenge involved in fully fleshing out a new aviation system. Because of these complications, it seemed more optimal to utilize staging, as it is a very tried mechanism of increasing fuel and weight efficiency.

It should be noted, however, that the idea of a helper plane does allow for more efficient reusability. In the case of mission failure, this could allow for another attempt at mission success to occur, as the plane could land and then be used again. However, due to the constraints of limited materials, it is not expected for another project to be possible anyways, and the team leaned towards betting on a more reliable first attempt as opposed to a better chance of success over multiple attempts.

3.2 Detailed Concept Development

The following is a detailed development of the intended mission design, where all characteristics of the model are fleshed out thoroughly. Any unexplained number (either uncited or not reasoned through qualitatively) is calculated below in the calculations section. Tables organizing the numerical data can be found below the discussion.

Development of Concept 2:

As Concept 2 was ultimately chosen, the idea started to evolve. Discussions began regarding how best to get Earth coverage using the cubesats. The initial idea involved four cubesats, with two going at a 45° incline and each going in a different direction. After further consideration, it was realized that one of the cubesats at an incline will be deployed from the kick stage in the opposite direction of the orbit, which would only cause the cubesat to lose velocity and end up re-entering into the atmosphere earlier than the other three; this left the concept with three cubesats.

From there, it was necessary to determine the orbital characteristics of the model. Inclination was partially restricted due to West Lafayette's latitude (L, 2012). Because inclination must be higher than latitude, this barred an inclination of 0 degrees, which would have allowed for full utilization of the velocity of Earth's rotation.

Originally, part of Earth's velocity was desired because it would make the rocket more efficient in its launch, but, as the concept developed, the need to revert to a polar orbit (as in Concept 1) became more apparent. Conducted research never indicated that the kickstage could launch satellites into wildly different orbits without its propulsion system- as such, the most reasonable option would be to launch the rocket down the middle of the intended orbital trajectories and then launch the cubesats accordingly. However, launching to a 45 degree orbit would land cubesats at a polar orbit and an equatorial orbit (admittedly, the cubesat could be launched at something closer to a 20 degree orbit instead, but the intention was to separate the cubesat paths as much as possible to cover more ground). An equatorial orbit is mostly pointless- as it continues orbiting the equator, the data received will be redundant. On the other hand, due to the rotation of the Earth, any other orbital inclination will continue to introduce more possible data (hence why a polar orbit, if one is willing to wait for long enough, would eventually allow coverage of the entire planet). To best work with this, the desired flight path became a polar orbit with no Earth help, but that allowed for the cubesats to be launched into 45 and 135 degree orbits. The payload mass is fairly small, so this didn't seem to present any serious issues regardless. The design decision table below summarizes the design decisions regarding the cubesat trajectories. The launch characteristics are also described in Table 13.

Table 7: Cubesat Design Decision - Qualitative summary of cubesat design choices.

Design Decision	Motivation
3 cubesats	Further cubesats introduce complexity and inclinations that counteract orbital velocity
Launch into polar orbit	Equatorial orbit produces redundant information after one pass, and cubesats should be split up as much as possible to diversify data

Next, to determine the proper altitude of launch, the camera performance of the cubesats needed to be considered. An altitude of 500 km allows for the camera to have a resolution of approximately 81cm^2 per pixel, which is optimal ("Chameleon Imager-CubeSatShop.com," 2019). This will translate to, considering the camera is to take 4K (4096 × 2160 pixels) pictures, each picture covering an area of 36,864m by 13,608m (Kim, Park, & Park, 2015).

To ensure that mission control won't lose information, data size needs to be taken into account. Considering the circumference of the earth is 40,075 km, and that one picture has a "height" of 13,608m (13.6km), 2945 pictures per orbit will be taken if a heat source is detected in every picture. This means the camera could potentially take 1.2GB worth of photos in one orbit. The data size of a 4K photo was estimated by taking photos on 4K smartphone cameras. Then, considering that communications with the cubesat are only possible when West Lafayette has a line of sight, the downlink time per orbit would be roughly 47.5 minutes (half the orbital period). Due to average satellite transmission speeds of about 3 MB per second, the cubesat could download about 5GB worth of 4K images at max capacity (Selva & Krejci, 2011). This means that mission control would be able to download all the images taken in any orbital period. Given these facts regarding camera and cubesat performance, the team can be assured that all data would be managed properly.

Moving forward, given that 500 km was determined to be optimal for camera performance, this defined the ΔV regardless of concept. The orbital characteristics that followed from that decision can be seen in Table 15.

It was then desired that the rest of the rocket characteristics be defined, which would be done be splitting the ΔV into stages, finding appropriate I_{SP} values and using the staging equations (programmed into MATLAB) to find the mass of each stage. This would ultimately define most of the rocket's characteristics, as it finalized the mass and performance.

To begin this process, it was decided that two stages would be used. Stages are optimal because they drop mass as the rocket uses fuel, becoming more efficient (Lopez, 2018). However, it's worth noting that staging can make a system more complicated, as it not only introduces a new engine with possibly a different design and propellant, but it also adds a failure point in the destaging mechanism. The benefits of staging, like with most things, suffer from diminishing marginal returns, which means it isn't useful to infinitely stage a rocket (even if that were feasible). To be reasonable (given the reliability and budget of a quick rescue mission), but to still pursue a more optimal initial mass, a two stage rocket was settled on.

It was then necessary to find a reasonable set of engines and propellants for the two stages. When looking into the benefits of solid vs liquid engines, it was found that a solid propellant engine is much less complicated, as well as lighter, than a liquid propellant engine. On the other hand, liquid rockets can be better controlled and have higher I_{SP} values. (Nakka, 2001 & Benson, 2014). Further, higher thrust is initially desired because the rocket is heaviest at launch, and solid propellant has a lower thrust to weight ratio (N, 2018). Given the limited resources available to the project, the first stage being a solid rocket to reduce weight and complexity made sense. However, it was undeniable that the maneuverability of a liquid rocket would be required when finalizing the orbit out of atmosphere. This lead to the design including a solid first stage and a liquid second stage.

To qualitatively sum up the decisions regarding staging and engines, refer to the table below.

Table 8: Staging Design Decisions - Qualitative summary of staging design choices.

Design Decision	Motivation
Staging – 2 stages	More efficient fuel consumption while limiting complexity
1st Stage: Solid Engine	More thrust/weight while in atmosphere; low complexity
2nd Stage: Liquid Engine	High I_{SP} and throttle control for orbital maneuvering

The I_{SP} values of the stage engines was determined primarily based on averages and what was believed to be reasonable given the resource constraints the project operates under. To determine the proper fuel to be used, energy densities of different fuel types was researched. For the liquid engine, RP-1, which is refined kerosene, had a lower density specific impulse than other fuels, such as RJ-5 and RJ-6, at 341.7 seconds (Rapp, 1990), but was commonly used in the industry as it greatly reduces soot, coke deposits, and a tarry residue compared to kerosene, preventing possible clogging of the engine (Braeunig, 2008). Because of this, and the fact that typical liquid engines use RP-1, it and liquid oxygen (as the oxidizer) was settled on. This is a "tried and true" combination for liquid propellants (Walker, 1996). Regarding solid propellants, based on the class rocketry notes and the fuel's high performance and long burn time, an ammonium perchlorate, hydroxyl-terminated polybutadiene (HTPB), and aluminum polymer was selected (Nikka 2001). This provided a density specific impulse of 250 seconds (Seitzman, 2003). Looking at SpaceX's Falcon 9, JAXAs H-IIA, and ULAs Delta IV rocket engines, a reasonable range of 300-480 (roughly speaking) (J, 2003 & Falcon 9, n.d. & U, 2013)was determined for a liquid I_{SP}; the value of 440s was chosen for this design. For solid rockets, based on average ranges put out by the AIAA, 270-300s seemed like a reasonable range for the I_{SP} values (Landsbaum, Salinas, & Leary, 1980). From there, 290s was used. These values can be found in Table 10.

Table 9: Fuel and Engine Design Decisions **-** Qualitative summary of fuel/engine design choices.

Design Decision	Motivation
Liquid Fuel: RP-1, Liquid Oxygen	A historically proven combination; cleaner than normal kerosene
Liquid I_{SP} = 440s	Estimation based on prominent liquid engines ranging from 300-480s
Solid Fuel: 18% Al, 71% NH_4ClO_4, 11% HTPB	Historically verified; high performance and long burn time
Solid I_{SP} = 290s	Estimation based on AIAA's range for solid rocket engines (270-300s)

To obtain rocket staging characteristics, inert fractions for each stage were needed. Based on class notes, the first stage, being a solid, would have an average f_{inert} of about 0.1 and the second stage, being liquid, would have an f_{iner} of .17. Typical ranges for f_{inert} support this (Akin, 2014). Finally, the payload mass was calculated as 54 kg, which was made up of three 3U cubesats and three kickstages. The cubesat weight was given as 5kg per U, and the 3U-sized systems were used to allow for proper equipment to support the camera. The kickstage mass is 3kg per unit (Pignatelli, n.d). Plugging in the necessary values to the ideal rocket equation, and parsing through possible values of f_1 (the fraction of ΔV used by stage 1) in the code (listed in Appendix A), optimal ΔV fractions and stage masses were finally developed. This determined the values listed in Tables 11, 12, and 13.

The rocket diameter was based upon the payload. The 3U cubesat has a length of 30 cm, meaning, with the cubesats placed in a triangular formation and with some extra space for the kickstages, the total diameter of the payload bay is 75 cm (see Figure 4 for a physical reference). The rockets stages themselves didn't need to be as large, so the diameter of the rocket was set to be 50 cm, or 0.5m. Utilizing this number, the height of each stage was calculated using the known propellent mass, diameter, and density of each fuel. The final dimensions were calculated to be a height of 3.7652m for the first stage, and 1.0097m for the second stage. The fairing has a diameter of 0.75m and a height of 1.1m (determined approximately when modeling in CAD). The nozzle height was also estimated during modeling, and is approximately .5m. This brings the total height of the rocket to 6.3749m. This can be seen in Figure 5 below. The sizing specifications are also listed in Table 16.

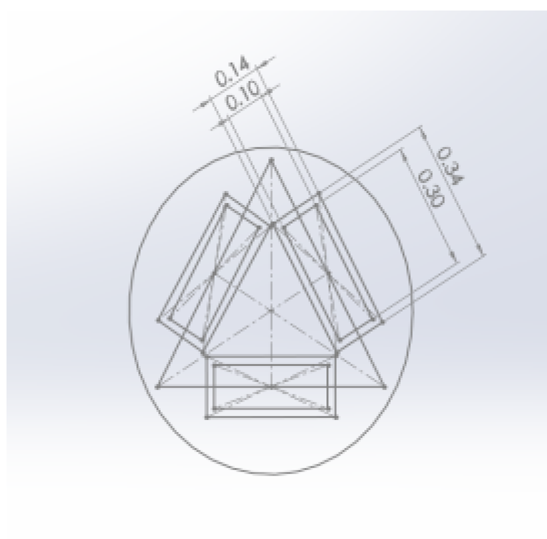
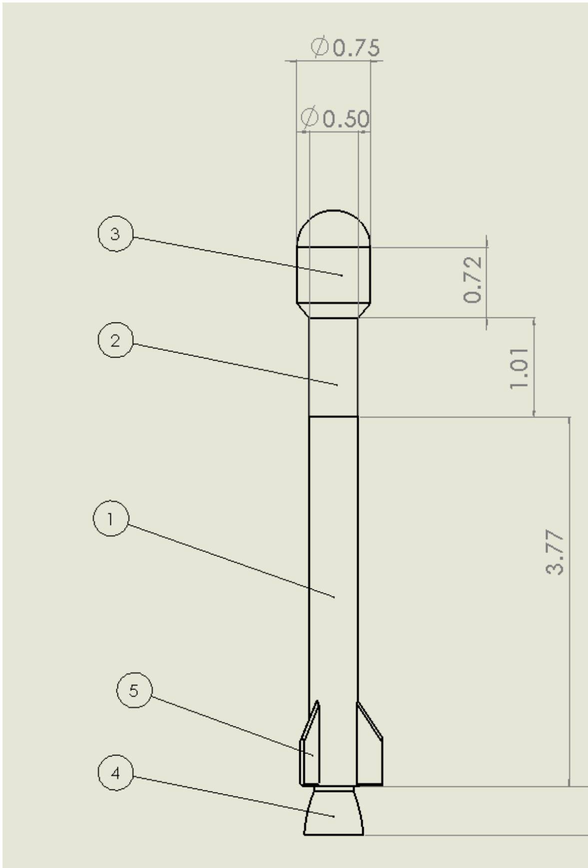


Figure 4: Fairing Cross-Section - A visual representation of the formation of the three kickstages placed on the rocket.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Stage 1		1
2	Stage 2		1
3	Fairing		1
4	Nozzle		1
5	Fin		3

Figure 5: Rocket Dimensions - A drawing showing rocket (with dimensions in meters). Each component is labeled.

Finally, for a rocket of this size, adding fins will help with the stability during launch. A common practice is to either add three or four fins; however, three fins is enough to provide the stability needed for the rocket. The clipped delta shape was chosen, as it is one of the basic forms of fins that aid in stability. Since the vehicle will travel at supersonic velocities, both the leading and trailing edge of the fin has to be a wedge shape (Nakka, 2001). Not much further detail was considered for the fin design, as it mostly escapes the scope of this project.

Notably, the structural integrity of the rocket was not very easily determined and found to be beyond the scope of this course. It is an important consideration for the project, but much more intricate design and simulation of the rocket would be needed to analyze it. Should the rocket use historically verified materials and practices, this should be reliable, but cannot be confirmed in the report.

A final rendering of the rocket's design can be seen in Figure 6.

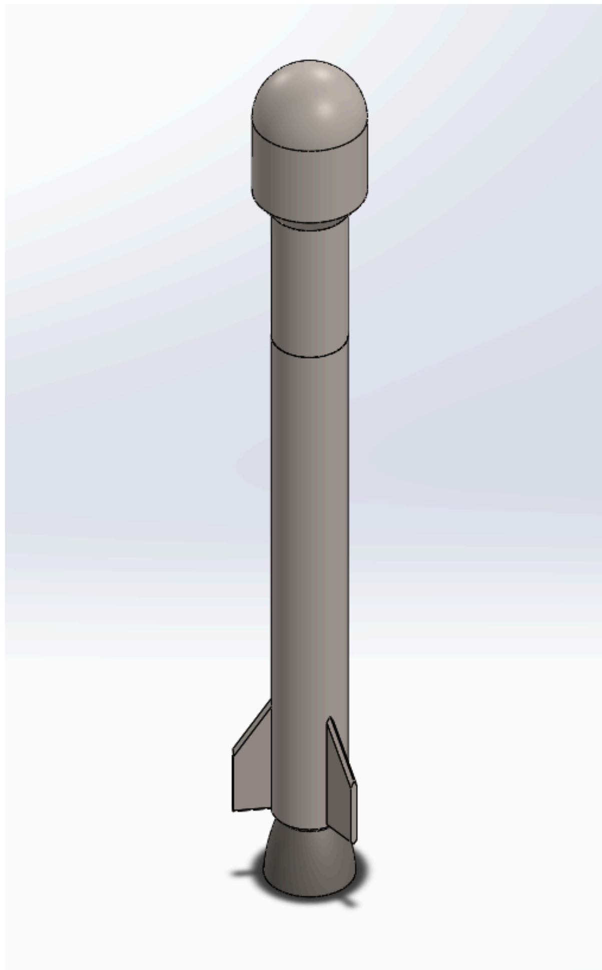


Figure 6: 3D Rocket Model - A simplified CAD model of the final rocket design.

This concludes the details regarding Concept 2's development. Detailed equations and calculations can be found below the listed tables.

Table 10: Rocket Engine Specifications - Specifications for rocket engine fuel data.

	Fuel	I_{SP} (s)	Fuel Density (g/cm^3)	Density Specific Impulse (I_d, Seconds)
Stage 1 (Solid)	18% Al, 71% NH_4ClO_4, 11% HTPB	290	2.04	250
Stage 2 (Liquid)	RP-1, Liquid Oxygen	440	0.80	341.7

Table 11: Rocket Mass Specifications - Specifications for rocket mass properties, based on stage.

	m_{prop} (kg)	m_{inert} (kg)	m_{pay} (kg)	f_{inert}	$m_{initial}$ (kg)
Stage 1	1482	164.66	380.53	.1	2027.2
Stage 2	271.02	55.51	54	.17	380.53

Table 12: ΔV Fractions Per Stage - Optimal ΔV fractions based on MATLAB calculations.

	ΔV Fraction
Stage 1	.59
Stage 2	.41

Table 13: ΔV Per Stage - Numerical value of ΔV for each stage

	Stage 1	Stage 2
ΔV	5376.2865 m/s	3736.0635 m/s

Table 14: Launch Characteristics - Angle specifications for the launch characteristics of the rocket.

Azimuth (degrees)	Latitude (degrees)	Inclination (degrees)
0	40.4259	90

Table 15: Orbital Characteristics - Orbital behavior of the rocket/each cubesat once desired altitude is achieved.

Altitude (km)	ΔV_{tot} (m/s)	Period, T (s)	T (min)
500	9112.35	5689.28	94.65

Table 16: Rocket Sizing Specifications - Calculated or estimated sizing specifications for rocket stages, nozzle, and fairing.

Primary Diameter (m)	Fairing Diameter (m)	Stage 1 Height (m)	Stage 2 Height (m)	Nozzle Length (m)	Fairing Height (m)	Total rocket height (m)
.5	.75	3.7652	1.0097	.5	1.1	6.3749

Equations:

Eq. 1) $V_{Circular} = \sqrt{\frac{GM}{r}}$

Velocity for a circular orbit. This equation is a variation of the vis viva equation, which is derived as follows:

Taking the total specific energy of the system, assuming only potential and kinetic energy are relevant:

$$E_t = \frac{1}{2}v^2 - \frac{GM}{r}$$

Total specific energy can also be calculated as:

$$E_t =- \frac{GM}{2a}$$

This definition is defined by the semi-major axis, a. Setting these two definitions equal to each other, the equation is:

$$\frac{1}{2}v^2 - \frac{GM}{r} =- \frac{GM}{2a}$$

Solving this for v:

$$v = \sqrt{2\frac{GM}{r} - \frac{GM}{a}}$$

Because a circular orbit is desired, r = a. Simplifying the expression above, the desired equation is finalized.

$$V_{circ1ular} = \sqrt{\frac{GM}{r}}$$

Eq. 2) $\sin(Az) = \frac{cos(i)}{cos(La)}$

The relationship between launch azimuth, launch inclination, and launch latitutde.

Eq. 3) $T = 2\pi\sqrt{\frac{r^3}{\mu}}$

Velocity can be stated as

$$v = \frac{2\pi r}{T}$$

In other words, the circumference of a circular orbit over its period. This is intuitive, as it represents the distance of an orbit over the time needed to complete it. From there, it can be set equal to the circular orbit velocity (see above) to obtain:

$$\sqrt{\frac{GM}{r}} = \frac{2\pi r}{T}$$

Solving for period, and assuming the constant μ = GM, the finalized equation is complete:

$$T = 2\pi\sqrt{\frac{r^3}{\mu}}$$

Eq. 4) $m_{prop} = \frac{m_{pay}\left[e^{\frac{\Delta v}{Isp\, g_o}} - 1\right]\left(1 - f_{inert}\right)}{1 - f_{inert}\, e^{\frac{\Delta v}{Isp\, g_o}}}$

Rocket propellant mass (assuming ideal rocket conditions).

Eq. 5) $m_{inert} = \frac{f_{inert}}{1 - f_{inert}} * m_{prop}$

Definition of inert mass for rockets.

Eq. 6) $m_{final} = m_{pay} + m_{inert}$

Definition of final mass for rockets (per stage).

Eq. 7) $m_{initial} = m_{final} + m_{prop}$

Definition of initial mass for rockets (per stage)

Eq. 8) $\rho = \frac{M}{V}$

Definition of density of a given substance

Eq. 9) $V = \pi r^2 h$

Definition of volume for a cylindrical tank for the solid propellant tank

Eq. 10) $V = \pi r^2 h + \frac{4}{3}\pi r^3$

Definition of a bulkhead tank. A combination of a cylindrical and spherical tank.

Calculations:

1. Launch Azimuth and ΔV:

$$Az = \sin^{-1}\left(\frac{\cos(90^{o})}{\cos(40.4259^{o})}\right)$$

Assuming a circular and polar orbit, it was decided to launch at an inclination of 90^{o}. The latitude of West Lafayette is 40.4259^{o} N (L 2012). Using this information about the inclination (i) and latitude (La), the azimuth was derived to be 0^{o}, which is straight North.

2. Desired ΔV (based on orbital velocity):

$$V_{Circ1ular} = \sqrt{\frac{GM}{r}}$$

$$V_{Circular} = \sqrt{\frac{(5.972 \times 10^{24} kg)(6.6740 \times 10^{-11} m^3 kg^{-1} s^{-2})}{6378.1 \times 10^3 m + 500 * 10^3 m}}$$

$$V_{Circular} = 7612.35 \text{ ms}^{-1}$$

The $V_{Circular}$ is the velocity of the selected orbit, with azimuth of 0 degrees and inclination of 90 degrees.

$$V_{Total} = V_{Circular} + V_{Loss} + V_{Earth\ Help}$$

V_{loss} is the ΔV lost to conditions such as atmospheric drag, and usually (according to class notes) falls between the values of 1.5 kms^{-1} and 2 kms^{-1}. $V_{Earth\ Help}$ is 0, since the rocket is launching directly North.

$$V_{Total} = 7.612.35 \text{ ms}^{-1} + 1.5*10^{3} \text{ ms}^{-1}$$

$$V_{Total} = 9112.35 \text{ ms}^{-1}$$

This is the total ΔV required for the mission when launching North with an azimuth of 0^{o}. This values is listed in Table 15 alongside the other orbital characteristics of the launch.

3. Orbital Period:

$$T = 2\pi\sqrt{\frac{r^{3}}{\mu}}$$

$$T_{Orbit} = 2\pi\sqrt{\frac{((6.38 \times 10^{6}) + 500000)^{3}}{(3.986 \times 10^{14})}}$$

$$T_{Orbit} = 5679.28 \text{ s OR } 94.65 \text{ min}$$

The amount of time it takes for the cubesat to make 1 complete orbit is 94.65 minutes. This value is listed in Table 14.

4. Mass Properties:

The total ΔV required for this mission, as shown above, is $9112.35ms^{-1}$.

Using the assumed f_{inert} for the first stage and second stage of, 0.1 and 0.17, respectively, this allows for the percentage of ΔV provided by each stage to be calculated. Equations 4 through 7 should be used to calculate the remaining variables.

Using the known values for f_{inert}, m_{pay}, and I_{sp} while iterating through different fractions of ΔV values, all of the mass characteristics could be calculated for multiple scenarios of ΔV fractions (that is, how ΔV was split up by stage). First, the rocket's 2nd stage masses must be calculated, and, after calculating $m_{initial}$, that value is used as m_{pay} for the 1st stage and calculate the remaining masses. The code then graphs these ΔV fraction values against the $m_{initial}$, and finds the most optimal mass for the ΔV fraction. The lowest initial mass represents the optimal ΔV for stage 1, which determines the respective optimal ΔV for stage 2. These calculations were iterative, and, as such, were done in MATLAB. The code can be seen in the Appendix A. Figure 7 shows the graph produced in this process.

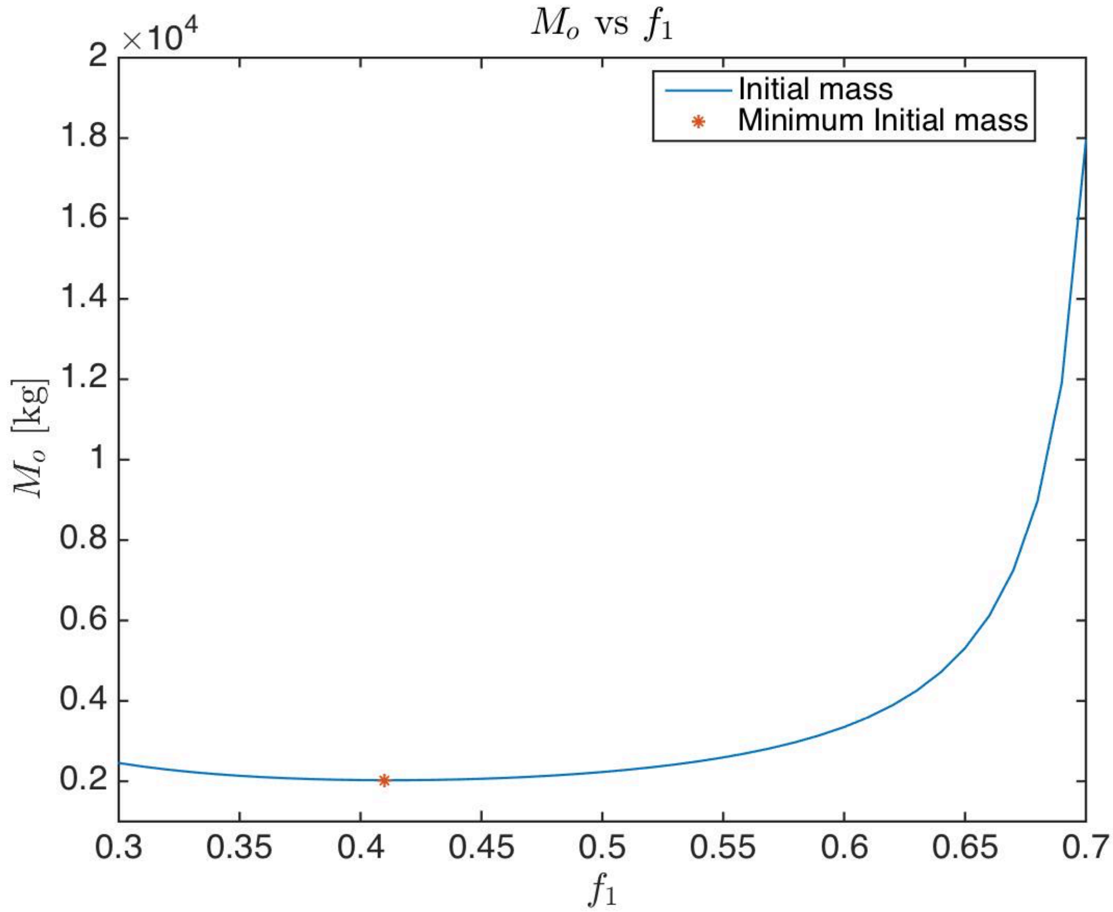


Figure 7: Optimal f_1 - A graph showing the relation between M_0 and f_1, the fraction of ΔV provided by the rocket's first stage, with the minimum point shown. Created in MATLAB.

ΔV for both stages of the rocket:

$$\Delta V_{tot} = \Delta V_1 + \Delta V_2$$

ΔV for first stage is:

$$\Delta V_1 = .41 \cdot \Delta V_{total}$$

Otherwise stated, 41% of the ΔV is used by first stage.

Thusly,

$$\Delta V_1 = 3736.06\, ms^{-1}$$

ΔV for second stage is then:

$$\Delta V_2 = .59 \cdot \Delta v_{total}$$

Or 59% of ΔV_{tot} is used by second stage, meaning:

$$\Delta V_2 = 5376.29\, m/s$$

The ideal ΔV fractions are listed in Table 12.

The final masses for this ideal ΔV fraction are:

$$m_{prop,\,1} = 1482\, kg$$

$$m_{prop,\,2} = 271.02\, kg$$

$$m_{prop,\,total} = 1753.02\, kg$$

$$m_{inert,\,1} = 164.66\, kg$$

$$m_{inert,\,2} = 55.51\, kg$$

$$m_{inert,\,total} = 220.17\, kg$$

$$m_{initial} = 2027.2\, kg$$

These values are also listed in Table 11.

5. Rocket Sizing:

These sizing calculations are based on the assumption that the rocket diameter is 0.5m, which was covered in the development of Concept 2. This allows the tank sizes and the overall rocket height to be calculated.

The first stage tank size can be found utilizing the m_{prop} for stage 1, 1482 kg. The density of the solid propellant is a mixture of 18% Al, 71% NH_4ClO_4, and 11% HTPB yielding a total density of 2004.7 kg/m^3 (Braeunig, 2008). Using the basic density equation:

$$\rho = \frac{M}{V}$$

$$V = \frac{1482kg}{2004.7kg/m^3}$$

$$V = 0.7393m^3$$

Now that the volume of propellant being used in the first stage is found, this value allows for the equation of the volume of a bulkhead tank to be applied.

$$V = \pi r^2 h$$

Since the radius of the rocket is known, based on the diameter and the volume of the rocket, the height, h, of the propellant tank can be calculated.

$$0.7393 = \pi(0.25^2)h$$

$$h_{1st\ Stage} = 3.7652\ m$$

The height of the first stage's tank is 3.7652 m. Based on existing engines such as the RS-68 used on the Delta IV (which had a length to diameter ratio of 2.14) and the Falcon 9's Merlin 1D engine (which had a ratio of 2.6), the ratio used for the length to diameter was assumed to be roughly 2.4. This yields an engine height of 0.6m. The total height of the first stage is 3.7652m.

Assuming that the rocket diameter is the same in stage two as stage one, 0.5m, the same procedure for calculating tank height is repeated to obtain the tank sizes for the second stage.

Second stage tank size can be found utilizing the m_{prop} for stage 2, 271.02 kg. The standard ratio of liquid oxygen and RP-1 is 2.56:1(Braeunig, 2008). This means that 194.86kg is liquid oxygen and 76.157kg is RP-1. The density of liquid oxygen and RP-1 is 1141 kg/m^3 and 820 kg/m^3, respectively (Braeunig, 2008).

Using the basic density equation:

$$\rho = \frac{M}{V}$$

$$V_{Liquid\ Oxygen} = \frac{194.86kg}{1141kg/m^3}$$

$$V_{Liquid\ Oxygen} = 0.1708m^3$$

Repeat the process for RP-1 to yield:

$$V_{RP-1} = 0.0929m^3$$

$$V_{total} = 0.2637m^3$$

Now that the volume of the propellant used for the second stage is known. With this value, the equation for the volume of a bulkhead tank can be applied.

$$V = \pi r^2 h + \frac{4}{3}\pi r^3$$

Since the radius of the rocket based on the diameter and the volume is the same throughout, the height of the second stage tank can be determined.

$$0.2637 = \pi(0.25^2)h + \frac{4}{3}\pi(0.25^3)$$

$$h_{2nd\ Stage} = 1.0097\ m$$

The height of the second stage's tank is 1.0097 m.

Finally, adding up all the different heights of the parts composing the rocket (including a fairing of 1.1m and nozzle length of .5m), one can obtain the total height, equal to 6.3749 m.

The sizing specifications of the rocket as seen in this section are listed in Table 16.

4 Conclusions

In this section, a summary and evaluation of the final design can be found along with some ideas for continuing the development of this rocket. There is also a review of the lessons that the team learnt while working on this project.

4.1 Design Evaluation

The system described in this report has a good chance at working. It was meticulously designed to satisfy the requirements set forth in the description and problem statement. The rocket will launch three cubesats to an orbit of 500 km to use thermal imaging to search for survivors of the zombie apocalypse. After calculating the ΔV required for this maneuver and what fuels would give us the best results, a two stage rocket was designed, with the first using a solid rocket motor and the second using an RP-1/LOX engine. We feel this design gives us the best chance of success compared to the other concepts generated in this report. Launching the rocket off of an airplane, as suggested in Concept 3, was found to not be a feasible option in the apocalypse scenario, and launching only one cubesat into orbit as suggested in Concept 1 does not have the redundancy that is desired.

There are some remaining risks that are out of the team's control and some that can potentially be controlled. There is always the risk that a launch will fail due to a zombie attack on the base, an adverse weather phenomenon, or unforeseen space junk that could cause the rocket to go off course or blow up. In this report, we have listed ways of minimizing the risks that these pose such as scrubbing the launch if there are high winds, but there is still a slight risk that something unforeseen happens that causes the launch to fail.

The launch vehicle satisfies each requirement set forth in the document. It is capable of carrying a 54 kg payload into space and launching three 3U cubesats into orbits of 500 km at different orientations. It was designed to use an efficient amount of resources and use historically verified systems. Lastly, the rocket was designed to have attitude control while flying to maintain a steady course and to achieve the desired orbit. The rocket meets all of these requirements and, in turn, has a great chance of success for launching the cubesats into orbit to hopefully find some survivors of the apocalypse.

4.2 Next Steps

If the team was to continue this project for another semester, we would look at integrating reusability into the design. To have the rocket able to be recoverable and flown again would decrease the resource demand on the survivor colony. It could have a high resource cost to develop, but will reduce the resources used and needed in the long term. The rocket could be designed to fly back to the launch site or it could parachute down to Earth and be recovered by one of the airplane teams.

Further, considerations such as the structural integrity or more precise engine design could also be delved into. This may include working with materials and simulations to withstand the stresses of leaving the atmosphere, or using CAD to properly model the inside of the rocket. These considerations were beyond the scope of this project, but would be important in an actual implementation.

Overall, these could be interesting challenges to research and explore in more depth.

4.3 Lessons Learnt

Throughout the span of the semester while working on this project, we have learned several lessons, with one of the most important being time management. Each week, when the team met, we would first go over what needed to be done during that meeting. At the end of the meeting, we would go over what needed to be done before the next meeting. This allowed us to work efficiently on the assigned tasks and maintain a schedule to keep us on track to finish this project on time and without too many late nights. Another lesson we learned was to have reliable and well documented sources. As we researched information, we ran into trouble with documenting our sources. We would not immediately cite our sources in text and that led to problems later with finding where we referenced the sources and which source was referred to.

Some technical lessons we learned while working on this project were the use of an iterative approach while designing. Because no idea is perfect as soon as it is created, the use of an iterative approach was extremely useful in creating our designs. At the same time, we found that, when using the iterative design process, we would need to go back to certain decided design aspects and update them when we ran into a problem further down the road. This meant that every design decision was not only molded to fit the decided designs before it, but also any design aspects after it.

Another technical lesson we learned was how to use the different rocket equations that we learned in class. Before using them in class and on this project, we had no idea how to use them or how they were beneficial in designing a rocket. Now that we are done with this project, it is clear how useful they are and we have a genuine understanding of how to use them. These were some of the lessons that we learned while working on this project. They will definitely be useful in the next few years of college and in life when we are designing actual rockets or systems that need to be thought through and well designed.

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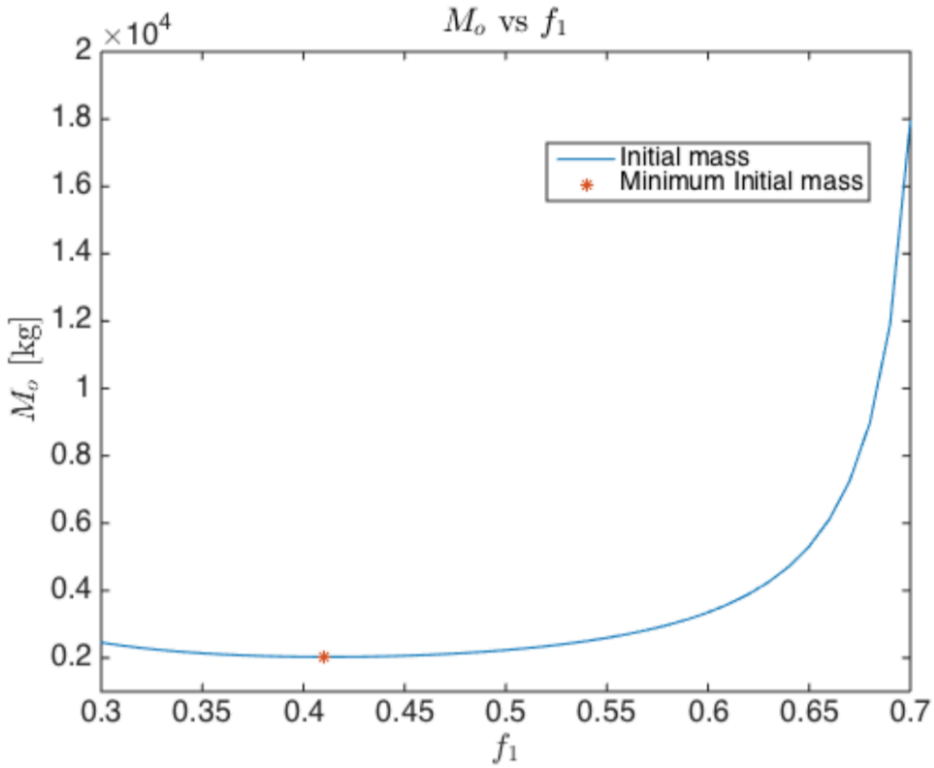
Appendix A: Matlab Code for obtaining percentage of ΔV for each stage and different masses of the rocket

```
clc; clear all; close all;

f1 = 0.3:0.01:0.7;

%We perform the calculations for each value of f1 between 0.3 and 0.55

for i = 1:length(f1)

    %We calculate the contribution to delta_V of each stage

    D_V1(i) = f1(i)*9112.35; %[m/s]
    D_V2(i) = (1-f1(i))*9112.35; %[m/s]

    %We start by the second stage, to get the payload of stage 1 (initial
    %mass of stage 2)

    Mprop2(i) = (54*(exp(D_V2(i)/(9.81*440))-1)*(1-0.17))/...
        (1-0.17*exp(D_V2(i)/(9.81*440)));
    Minert2(i) = 0.17/(1-0.17)*Mprop2(i);

    Mpayload1(i) = Mprop2(i)+Minert2(i)+54;

    %Now we use this value to compute propellant mass and inert mass for
    %stage 1

    Mprop1(i) = (Mpayload1(i)*(exp(D_V1(i)/(9.81*290))-1)*(1-0.1))/...
        (1-0.1*exp(D_V1(i)/(9.81*290)));
    Minert1(i) = 0.1/(1-0.1)*Mprop1(i);

    Mo(i) = Minert1(i)+Mprop1(i)+Mpayload1(i); %Initial mass in kg
    Mprop(i) = Mprop1(i)+Mprop2(i);

end

[Mo_min,index] = min(Mo);
f2 = 1 - f1(index);

disp('Minimum initial mass [kg]:');
disp(Mo_min);
disp('f1:');
disp(f1(index));
disp('f2:');
disp(f2);
disp('Mass of propellant required for stage 1 [kg]:');
disp(Mprop1(index));
disp('Mass of propellant required for stage 2 [kg]:');
disp(Mprop2(index));
disp('Total Mass of propellant required [kg]:');
disp(Mprop(index));
disp('Inert mass required for stage 1 [kg]:');
disp(Minert1(index));
disp('Inert mass required for stage 2 [kg]:');
```

1

```
disp(Minert2(index));
disp('Total inert mass required [kg]:');
disp(Minert1(index)+Minert2(index));

figure()
plot(f1,Mo)
hold on
plot(f1(index),Mo(index),'*')
hold off
legend('Initial mass','Minimum Initial mass','Location','Best')
xlabel('$f_1$','Interpreter','latex');
ylabel('$M_o$ [kg]','Interpreter','latex');
title('$M_o$ vs $f_1$','Interpreter','latex'); set(gca,'FontSize',16);
ylim([1000 20000]);
saveas(gcf,'Mo vs f1','jpg');
```

```
Minimum initial mass [kg]:
   2.0272e+03

f1:
    0.4100

f2:
    0.5900

Mass of propellant required for stage 1 [kg]:
   1.4820e+03

Mass of propellant required for stage 2 [kg]:
  271.0203

Total Mass of propellant required [kg]:
   1.7530e+03

Inert mass required for stage 1 [kg]:
  164.6626

Inert mass required for stage 2 [kg]:
   55.5102

Total inert mass required [kg]:
  220.1728
```



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Appendix B: Weekly Update Emails

Week 1: 1/11/19

-This week, the team created our team name (Project Aurora), created our mission statement, and drafted our needs and requirements for both the cubesat and our rocket.
-Next week, we plan to brainstorm solutions and modify previous work once current issues are resolved.

-We had issues regarding: specifications for the cubesat, mission statement, budget/materials, and citation of sources

-We revised our mission statement and needs, as well as starting work on our preliminary risk assessments
-Next week, we will continue a more in-depth risk assessment and other requirements as they come up
-We are concerned about where we are supposed to upload our document link on BlackBoard

Week 2: 1/18/19

-We revised our mission statement and needs, as well as starting work on our preliminary risk assessments
-Next week, we will continue a more in-depth risk assessment and other requirements as they come up
-We are concerned about where we are supposed to upload our document link on BlackBoard

Week 3: 1/25/19

-This week, we updated risk assessment with information we went over in class.
-We plan on specifying the probability of risk once we can talk about specifics in class
-We would like to know how to quantify the probability of risks for the NASA risk chart.

Additionally, we were unsure where to submit the link to our document on BlackBoard until just recently. It is now uploaded. We apologize for the inconvenience and understand any decisions made regarding the submission.

Week 4: 2/1/19

-This week, we took the orbital formulas given to us in class and calculated velocity and period for a cubesat launched into a polar orbit. We also listed and derived all the equations relevant to these calculations, with the exception of the relation between inclination, latitude, and azimuth. These calculations were relevant to one of our concepts.

-Next week, we will flesh out 3 concepts for our future designs.

-We have concerns about deriving the relation for launch azimuth. It seems like its derivation may be a bit beyond what most derivations at this level will be.

Week 5: 2/8/19

-This week, we brainstormed concepts for our mission design. Although this is our first time recording these ideas, we had been discussing these ideas in previous meetings without documenting it, so we also included developmental history of each, as well as specifications.

-Next week, we will continue to refine these concepts.

-We do not currently have any concerns.

Week 6: 2/15/19

-This week, we received comments from Prof. Marais. We addressed some of them, and we are still researching to address the others. We also attempted to develop an algorithm to calculate the desired transfer perigee for our launch, albeit unsuccessfully.

-Next week, we plan to attend office hours to address issues regarding our concept development section (which Prof. Marais told us was not the way it should be) and to hopefully get help fixing our perigee algorithm.
-We have concerns regarding the two things we will work on next week, but hopefully those can be addressed in office hours.

Week 7: 2/22/19

-This week, we continued to address some of our issues that based on comments placed in our document. We cleared up some requirements and will continue to develop a relationship between our requirements and developed solutions. We also worked on the delta V calculation, but have discovered (by means of code) that the most efficient method of launch is directly to our desired orbit. We went to office hours to discuss whether or not this was accurate, and are waiting on a response on the issue.
-Next week, we hope to finalize the explicit relationship between our requirements and generated concepts. We will also continue to optimize our mission. With any luck, we can also calculate our delta V.
-We still have concerns with our delta V calculation, but it should be addressed soon. We also emailed Prof. Marais to ensure we correctly fixed our mission in the way she desired (based on her comments).

Week 8: 3/1/19

-This week, we discussed the further specifications of our vehicle and resolved some issues regarding cubesat requirements. We further fleshed out our concepts and our continuing to add to our thought process towards optimal solutions. We also began simulating our project in the STK software, though (as beginners) we did not make much progress yet. Not a lot was changed in our document, but we discussed a lot regarding the optimal orbit of the cubesat, cubesat resolution, desired file type and date transfer, etc.

-Next week, we will work more on the VotW than our design project, but we still intend to continue working on figuring out the specifications of the STK simulation program and on our concepts such that we can begin crafting more details for the project.
-We don't currently have any questions other than the velocity concern we had last week, which is being addressed by through communication with the TAs.

Week 9: 3/8/19

-This week, because many of us would be on break during our normal meeting time, we all agreed to make progress on our VotW roles separately.

-When we get back from break, we plan to finalize our VotW project and begin working on the design project again. We will continue assessing solutions to problems such as cubesat and rocket specifications, and will work with the ideal rocket equation given our delta V.

-We don't currently have any questions/concerns.

Week 10: 3/23/19

-This week, we put finishing touches on the VotW paper and presentation.

-Next week, we will work on the Project Design and start research on engine and stage development with weights.

-We do not have any question for now.

Week 11: 4/11/19

-This week, we worked towards fully fleshing out our rocket. Using the new equations for Isp that have been introduced, we worked towards mass and staging specifications.

-Next week, we plan to continue work on the rocket specifications.

-We have a few concerns: Firstly, we would like to know how to choose an optimal Isp/engine. We have access to the most common ranges for Isps, but are unsure how to justify particular choices. We would also like to know if a "check-up" orbit in LEO is a good idea- a comment on page 16 of our document details our concerns. Finally, we are unsure how to find the inert mass fraction of the rocket.

Week 12: 4/12/19

-This week, we made a lot of progress solidifying our concepts. We researched rocket engines and staging and have now defined our optimal stage masses and engines.

-Next week, we want to flesh out our risk section.

-We don't have any specific questions, but we do want to see the feedback on the report as soon as possible so we know what aspects we need to improve.

Week 13: 4/18/19

-This week, we finalized the specifications of our rocket and cleaned up our document. We wrote the conclusions and are still organizing the complete documentation of our concept development, although all content is there (and just needs to be formatted and organized).

-This weekend and hopefully very little of next week, we will finalize our report document. We will then record our video.

-We do not have any questions at this time.