Summer 2022

CO2 Based Parachute Deployment

Anthony M. S. Settlemier
The University of Akron, ams593@uakron.edu

Nicholas Motter
The University of Akron, ndm55@uakron.edu

CO2 Based Parachute Deployment

Senior Design Project

Advisor: Dr. Daniel Raible

Nicholas Motter
Department of Mechanical Engineering
The University of Akron
Akron, USA
ndm55@uakron.edu

Anthony Settlemier
Department of Mechanical Engineering
The University of Akron
Akron, USA
ams593@uakron.edu

Table of Contents

Ch 1: Introduction and History

This project was undertaken as a research and design project for the Recovery section of the Akronauts Rocket Design team, and relates to the deployment method utilized for initial drogue parachute deployment. However, recent rockets have demonstrated some issues with this technique.

The style of black powder based deployment that past Akronauts rockets have featured took the form of a charge cup based system. In this case a measured charge of black powder was packed into a short cylindrical (the aforementioned charge cup) and wired with an electronic match as a means of ignition. This system was then attached to an aluminum bulkhead separating the electronics bay from the drogue chute bay. An example of the relative layout of these bays is displayed below

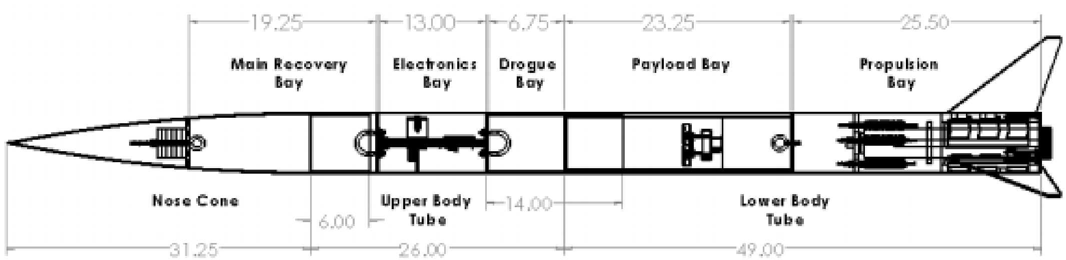

Figure 1: Example Rocket Layout

Note the adjacency of the drogue and electronics bays. Two charge cups, one primary and one redundant, were then wired to the stratologger, a device used by the rocket to track the attitude of the rocket and thereby trigger the parachute deployment system. Once the stratologger detected that the system had reached apogee, then it would send current through the electronic match, igniting the black powder charges and separating the bays.

The issue with this concept arises with the increasing altitude and size of Akronauts rockets. As of the writing of this paper the team has sent rockets to an altitude of 20k ft, and black powder has begun to demonstrate unreliable characteristics in this lower pressure environment. Now, contrary to the initial instinct of those not familiar with the substance this is not due to any issues with low oxygen levels at altitude hampering the combustion process as black powder is self-oxidizing. Rather, the lower pressure at these altitudes seems to be slowing down the combustion propagation, and this has begun causing issues with deployment.

The main area of concern has to do with damage to the parachutes. In past and present black powder based designs the parachutes have been wrapped in Kevlar bags in order to protect the temperature delicate nylon material from the hot gases caused by black powder. However, the slower combustion seen at higher altitudes has sometimes allowed the hot gases sufficient time between ignition and bay separation to at least partially penetrate the Kevlar bag protection and damage the parachutes themselves. This issue was further exacerbated by the increasing size of Akronauts rockets, demanding larger parachutes and thereby larger bays and black powder charges to separate those bays. All these factors combined to make it apparent that there should be investigation into alternative methods of deployment.

Ch 2: Design

Utilizing CO2 based deployment for rocket recovery, it is possible to more reliably deploy parachutes and more importantly, deploy them undamaged. Through many design iterations a design was landed on based on simplicity and reliability.

One of the downsides of CO2 that had to be considered was the lower pressure impulse compared to black powder. To account for this lower impulse, the design combined concepts from other rocket parachute deployment methods meant to increase the pressure retention inside the rocket. The design includes a puck that acts as a solid movable piston that helps to contain the pressure released from the CO2 cartridges. This ensures there is a high enough pressure differential to produce enough force to shear the nylon pins that keep the rocket together during ascent. This puck design stems from another recovery method called a “fire piston” where a pneumatic cylinder is rapidly pressurized by a black powder charge to deploy the parachute. The “fire piston” is vertically expensive and mass expensive when it comes to rocketry.

Another constraint of the design was horizontal area. The rocket team utilizes between 4-inch diameter rockets and 8-inch diameter rockets. To account for all rocket diameters, as this system will be easily scaled to larger rockets, the constraint was assessed and made so the system was designed for a 4-inch rocket diameter.

Initial Concept Selection

Of course, CO_2 was not the first and only idea for how to accomplish this project. To make sure there would be an adequate number of options one of the first things done was brainstorm concepts that would all potentially accomplish the task of separating the stages. There were many additional ideas floated but here are some of the concepts.

Firstly, there was the idea of utilizing a piston-type mechanism at the end of the bay to separate the sections. As this was from the initial brainstorming stages it was a vague idea but had several immediately apparent flaws. Firstly, any such system would limit cross sectional area near the end of the bay through which the parachute is designed to exit. This meant that the parachute or its lines might become caught on the way out of the rocket preventing proper deployment. Additional issues come in the form of difficulties securing any potential mechanism to the structure of the rocket, as well as properly wiring the system. In the end this alternative was dismissed largely due to being overly complicated for the objective's purpose.

A second concept took the form of a servo or motorized system; however, this was dismissed due to it not being feasible at the desired volume and weight. There were additional problems similar to those of the theoretical piston system, in that it would be difficult to secure.

CO_2 was an early entry in the idea generation stage for several reasons. Firstly, the Recovery team had been considering utilizing CO_2 for some time, and there was some baseline research that would be available for use. In fact, the team had begun experimenting with a commercially bought system known as the Raptor. However, this system still utilized black powder as its mechanism of breaching the CO_2 canister's seal, and thus a purely mechanical solution was still preferable.

In addition to this CO_2 has a few positive aspects that made it desirable in comparison to other methods. Firstly, the largest objects involved were anticipated to be the CO_2 cannisters themselves, which possessed standardized connection points in the mass range the team was investigating. This meant that not only would the largest occupier of volume be estimated at the earliest stages of the project, but also that it would not be necessary for it to occupy space in the parachute bay. Instead, it was recognized early on that the cannisters could be mounted directly into the bulkhead between the electronics and parachute bays. In fact, due to the methodology of mounting the electronics, the cannisters could be mounted in the electronics bay itself, saving valuable volume and allowing for far greater space efficiency than the other systems.

Related to this, CO_2 had the benefit of being easily installed. This was due to the mechanical nature of systems, once the first assembly was complete the system would be incredibly labor efficient. Due to this there would be little necessary preparation for an individual launch, merely necessitating the attachment of cannisters and connection of the electronic wiring. Additional benefits included reusability, as the only part of the system requiring replacement would be the cannisters, as well as the scalability of the mechanism, as scaling would be as simple as increasing or decreasing the size of utilized cannisters.

Design Iteration

Once it was determined that CO_2 would indeed be the selected choice, the process of revising the designs began. It was known from experience with the Raptor system that the CO_2 canister's seal could be broken utilizing a needle type object, and thus that aspect was carried over. Other early features included the use of a solenoid actuator as the means of force production.

However, there were a few other options considered in the solenoid's place. One of the first ideas floated was to have a mechanically secured preloaded spring be attached to a needle, with a latch being pulled in order to activate the device. There were three main issues with this method. Firstly, such a system would be vulnerable to vibrations during the rocket's ascent. Secondly, this mechanism would involve undesirable amounts of mechanical complexity, as an additional method to release the securing mechanism would be required. Finally, this mechanism would be difficult and borderline dangerous to install, as the spring would have to be loaded and the system installed before launch, and there would be a constant, if small, risk of it deploying prematurely.

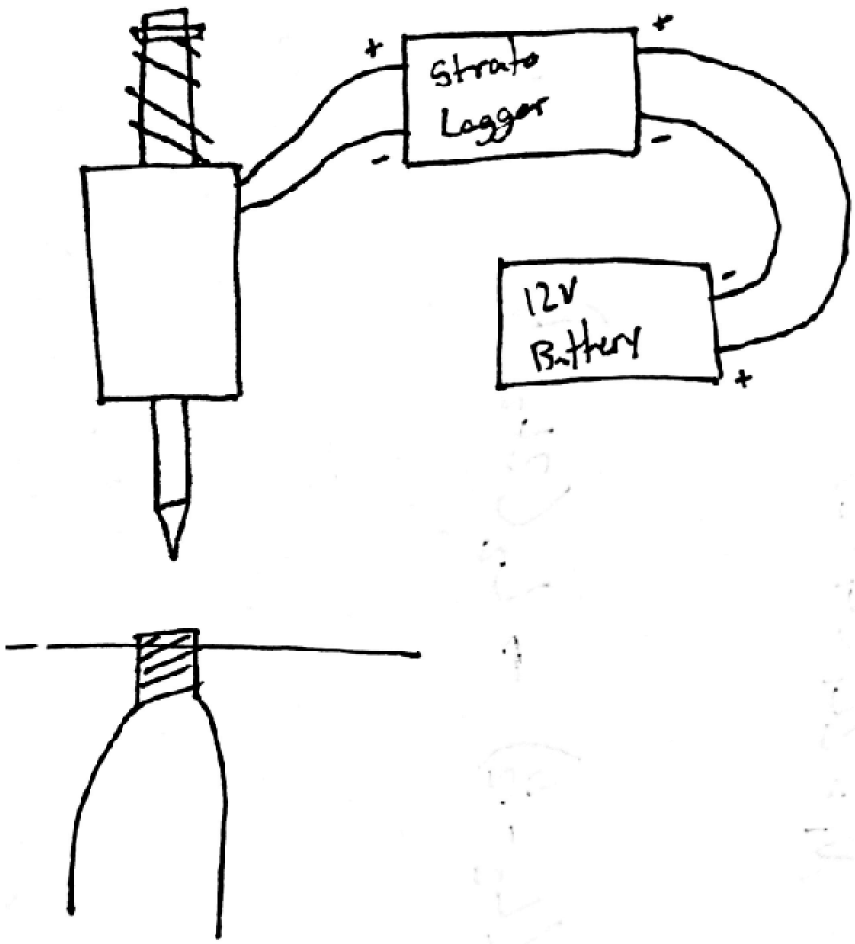

Figure 2: Concept 1

Figure 2 refers to one of the first concepts that followed along the same lines as the current design iteration. Notable characteristics are the vertical needle mounting, the needle shape, and the presence of the solenoid as the primary means to force generation. However, it was noted to have several issues that necessitated changes.

While it would be acceptable for a stationary system to possess a vertical needle alignment, this system will be composing a subassembly inside a rocket, and thus, is expected to be accelerated at several times Earth's gravity. As such, it was anticipated that the solenoid's spring would not be enough to prevent the needle from contacting the CO2 canister's seal upon launch. This would be due to Newton's 1st law, as the impactor needle would require a force from the spring capable of accelerating it at the same rate as the main body of the rocket. Due to this concern, it became clear that an alternative method of needle mounting would be required. This leads into the second iteration of the design.

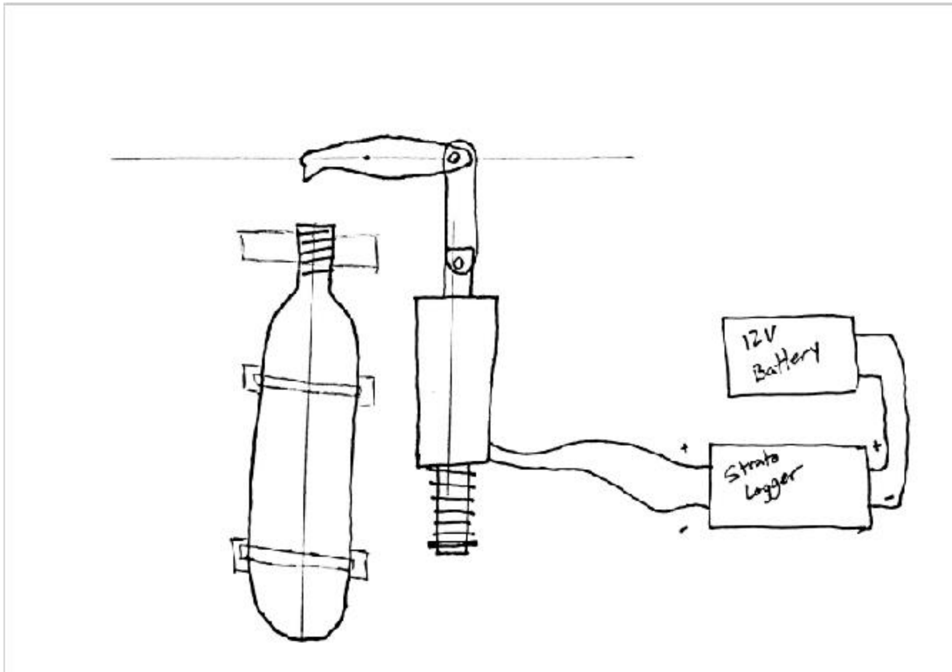

Figure 3: Concept 2

To address this the location and alignment of the solenoid was altered. In this case it was moved to the opposite side of the bulkhead. This alignment required the addition of a lever arm connection to redirect motion onto the seal.

However, this design had its own issues, this time with sealing. Due to the lower impulse of CO2 when compared with black powder, it was important to limit the amount of volume the gas could expand to. The previous design located the mechanical components on the recovery bay side of the bulkheads, meaning that the only components that would have to be sealed on the bulkhead were the wiring for the electronics and the connection points of the cannisters themselves.

The issues with the second design arose with the realization that due to the arm mechanism being a moving body, it would be far more difficult to seal than the static components such as the wiring or cannisters. Some solutions were explored, such as O rings slotted into the hole in the bulkhead the arm would be traversing, but this mounting method was eventually dropped in favor of the next iteration of the design.

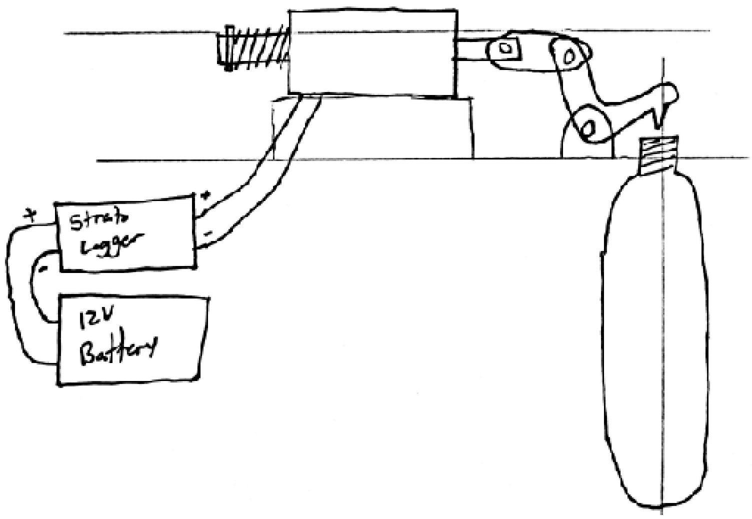

Figure 4: Concept 3 (near final)

Figure 4 describes the most recent iteration of the system, and illustrates two of most important alterations to the system, though additional features were added later that will be explored in the details section of this report.

To address the issue of sealing from the previous design, the mounting method was altered to be horizontal in nature and mounted of the parachute bay side of the bulkhead. The concept of a hinge arm was retained, but was altered to better account for the solenoid being oriented perpendicular to the CO2 cannister. This relocation meant that both of the major issues with the previous iteration of the design, the pin making contact and the sealing of the bay, were addressed. It was also decided that the all electronics should be integrated into the rocket's electronics bay, as there is preexisting mountings and designs for the mounting of batteries and similar.

Additional things to note with this design lie in the positioning of the solenoid and lever arm. Due to the limited cross sectional area of the rockets, the horizontal solenoid mounting method had to take the limited space into account for both the solenoid arm being at maximum and minimum extension. Thus while the design for the four inch rocket is limited in the size of solenoid that can be integrated, larger rockets may scale the solenoid accordingly with the amount of force that is required.

Design Details

Assembly

With the main characteristics of the system identified, it becomes time to go over the system as a whole. The completed system functions much as described in the third design iteration, with the added note of an added piece to connect the solenoid and impactor, as the addition of a plug to capture the CO2 gas as it is released, the reasons for which will be expanded upon later in this report.

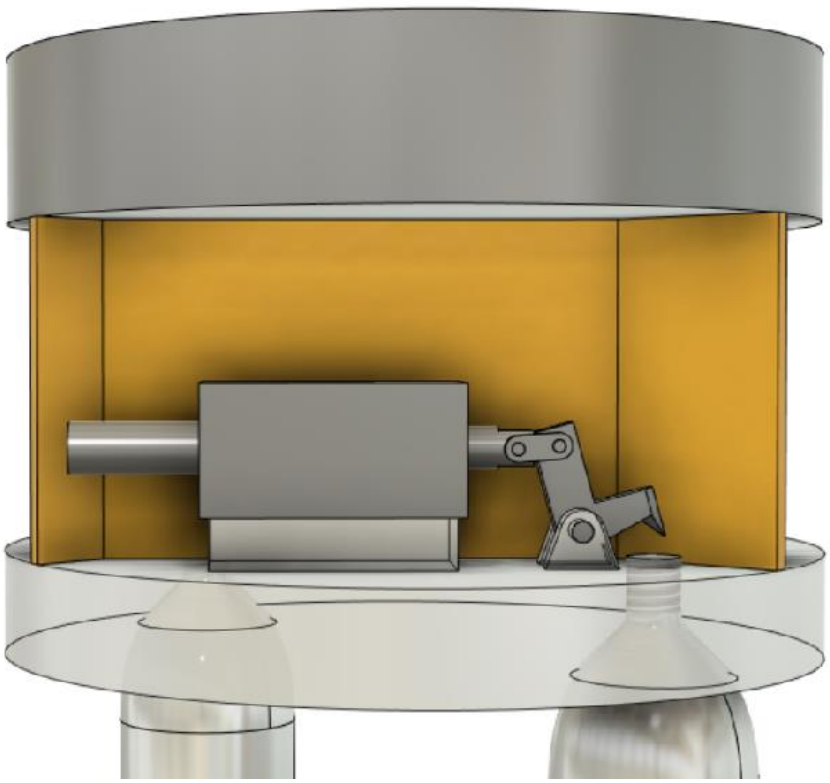

Figure 5: Image of Assembly

The model displayed above is that of the system being placed within a 4 inch rocket and fully extended to rear, displaying that the system is indeed capable of functioning within this constrained space. The system is designed with a solenoid capable of delivering a force of 5 N, which then applied at the miniscule tip of the impactor allows for the aluminum seal of the cannister to be pierced. The assembly as a whole follows a rather straightforward series of events that is demonstrated in the function diagram below

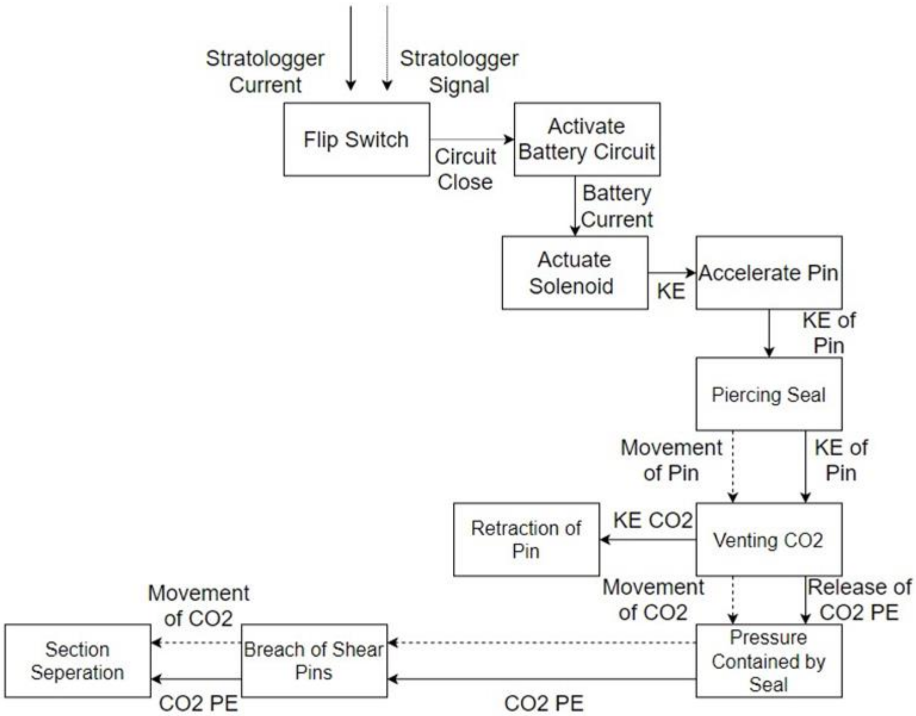

Figure 6: Function Diagram

This illustrates the standard series of events, from initial signal received from the stratologger to full separation of the parachute section. It should be noted that the diagram does not display the activation of the redundant charge, which is located on the opposite side of the yellow section division present on figure #. This is due to the redundant charge following the same series of events, simply at a time delay of under a second.

Impactor shape

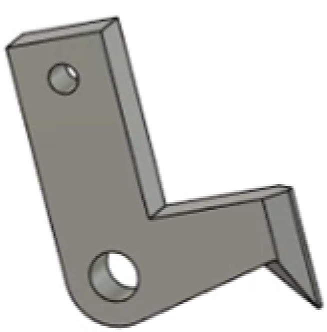

Figure 7: Wedge Impactor

As reviewed earlier, there were multiple iterations of the seal impactor before the final design. For optimal performance it was determined that the impactor should be machined out of metal, preferable a hardened steel in order to increase part life of the edge as a preventative maintenance measure. Additionally the added mass of utilizing metal will allows for more kinetic energy to be delivered at point of impact. Properly machined this impactor is anticipated to have no issues penetrating the canister seal.

This design possesses two connection points, the first at the top of the part and another near the bottom. The top connection point connects to the inter part link, and is the primary point of force transfer to the impactor. The bottom connection point serves as a hinge joint, allowing the L shaped impactor to transfer the horizontal motion of the solenoid into a vertical motion at point of impact with the seal.

Utilizing a wedge-shaped impactor, the risk of the impactor being lodged into the throat of the canister is minimized as the wedge will drag through the burst disk and rip it. Compare this to a needle impactor which in an edge case could get stuck in the throat and reseal the canister. This edge case could cause failure to deploy and result in total vehicle destruction.

Solenoid

A solenoid in its most basic form is a coil of wire and a ferromagnetic core. When excited with a voltage the coil of wire becomes an electromagnet and pulls the ferromagnetic core to the center of the coil. This device will then create a force proportional to the distance of the core to the center of the wire coil. The solenoid that was selected was capable of 5N of force at full extension (10mm). The selected unit, the JF-0530B, is a spring assisted solenoid. The spring keeps tension and allows the solenoid to rest in the retracted position. This feature also helps to resist unintentional deployment due to vibration and G-force sustained during launch.

Implementation of Plug

Utilizing a plug allows the pressure from the low impulse CO_2 to be captured. In early testing the CO_2 lacked the initial pressure spike, or impulse, needed to eject parachutes. This is attributed to the gas being allowed to diffuse through the parachute bags and ultimately to the outside of the rocket. Compared to black powder with an initial impulse much higher than CO_2 these impulse issues have never been present. By implementing a plug, the recovery bay of the rocket can essentially be turned into a pneumatic cylinder. Thus, capturing the work of the CO_2 canisters and allowing the necessary force for ejection to develop over a longer period. Additionally, the plug will limit the amount of volume the CO_2 gas will have available to expand into. As stated earlier the gas was diffusing into the parachute as well as exiting the rocket. Since the plug is installed below the parachute this means that instead of diffusing the gas instead is pushing against the plug which is itself pushing against the parachute.

The plug itself is designed to be composed of 3d printed material, likely PLA. This is due to several factors, including manufacturability, weight, and also the lower friction characteristics of the material. The plug itself will not bear any mechanical load besides the pressure from the CO_2 and is designed to allow the parachute shock cords to pass through the plug by dividing the shock cords into two sections, one before the plug and one after. These cords are joined by a metal fastener that passes through the plug. Currently this fastener is designed to have two U bolts connected to each other through the plug, though there is a secondary design utilizing an eye bolt instead. The reason these fasteners are employed is the 3d printed material utilized in the plug itself is nowhere near strong enough to withstand the forces present on the shock cord, and thus the fasteners were included to remove this load from the plug entirely.

Sealing Methods

The plug itself was deemed not sufficient to contain pressure itself while inserted into the recovery bay. The implementation of a sealing surface adds additional redundancy and confidence the parachutes will be deployed effectively. It was deemed that an O-ring would add unnecessary friction and inflate the size of the CO_2 canisters by requiring a greater force to move the plug. Another solution was theorized and implemented as shown below. The concept here imitates a self-sealing one-way valve where a thin flexible plastic sheet is inserted into a groove designed into the plastic plug. This would maintain easy assembly and placement of the plug pre-launch, but also allow a pressure induced seal from below the plug. The idea is that when the pressure increases below the plug the plastic sheet will be pressed to the sides of the bay and create a low friction movable gasket along the rim of the plug.

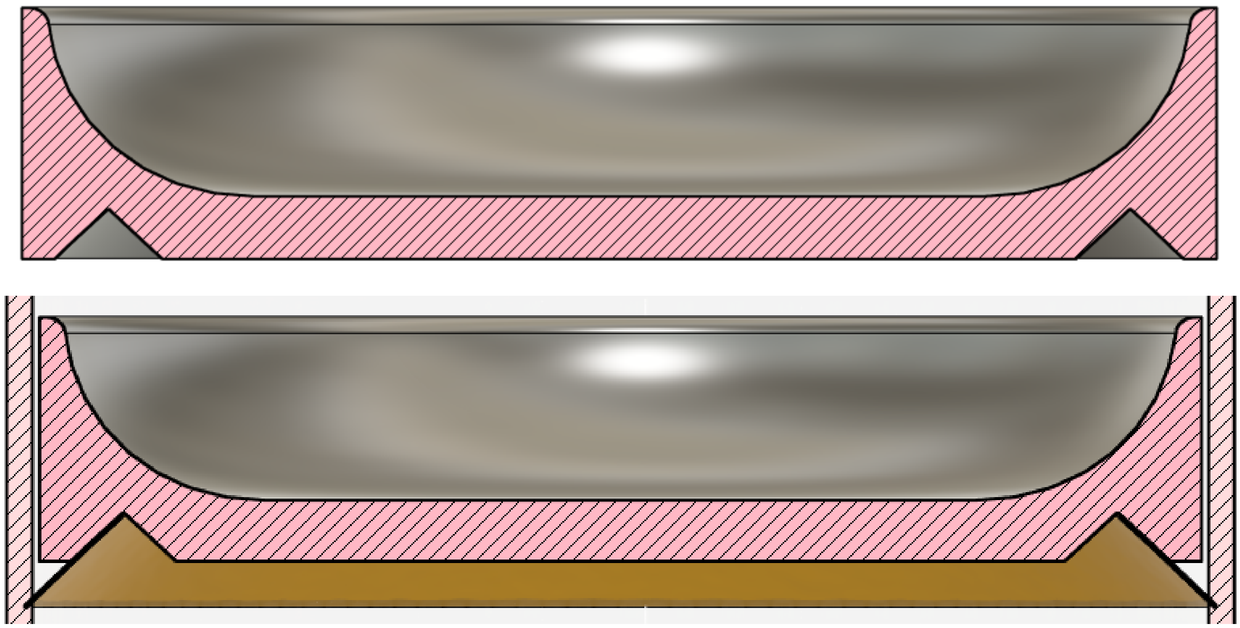

Figure 8: Illustration of Sealant

Electonics (links to stratologger, explanation of potential/optional additional battery circuit

Another constraint for this project was the use of the stratologger. This is the device that must be used along with minimal other components to determine when the recovery system will be triggered. This device is within the constraint list due to the nature of the rocket competitions the rocket team participates in. The recovery deployment component is a trusted and reliable tool for recovery deployment and is allowed in all competitions the team competes in. The stratologger raises concerns for utilizing a solenoid for deployment as this component is designed to ignite electronic matches meant to be utilized with black powder. This issue can be overcome by using a higher power battery with a higher voltage than what is typically used. Based on the data sheet the stratologger can accept a voltage up to 16V and deliver up to 10A based on the battery connected. What was initially thought to be an issue due to lack of information turned out to not be an issue based on the specifications in the data sheet.

Part Connection Methods

Any mechanical system requires points of contact and means to control part interaction, and this design is no different.

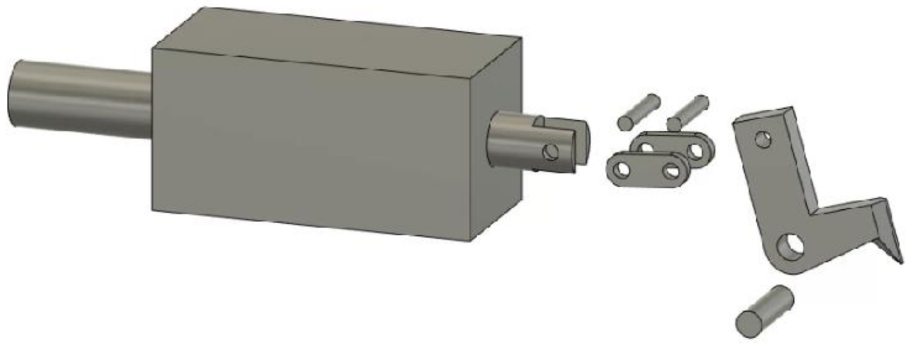

Figure 9: Joints

The majority of connection points in this design make use of hinge joints, allowing for both translation and rotation. These joints are designed to be secured with metal pins. It is important to note the presence of the central piece between the solenoid on the left and the impactor on the right of the above image, as without it the design would jam due to the impactor possessing vertical motion through its rotation and the solenoid being unable to move in that direction.

The solenoid itself will be secured with a 3d printed clip system, with holes placed to match with the screw slots in the back of the solenoid. The clip will secure directly into the bulkhead utilizing threaded holes going through half the bulkheads thickness (0.25 in) in order to maintain the seal between sections. In addition to the clip the bottom of the solenoid will be attached to the bulkhead section by making use of a rubber cement applied to the contact surface. The reason for the use of this adhesive has to do with vibrations, as it will assist in dampening the vibrations applied to the solenoid.

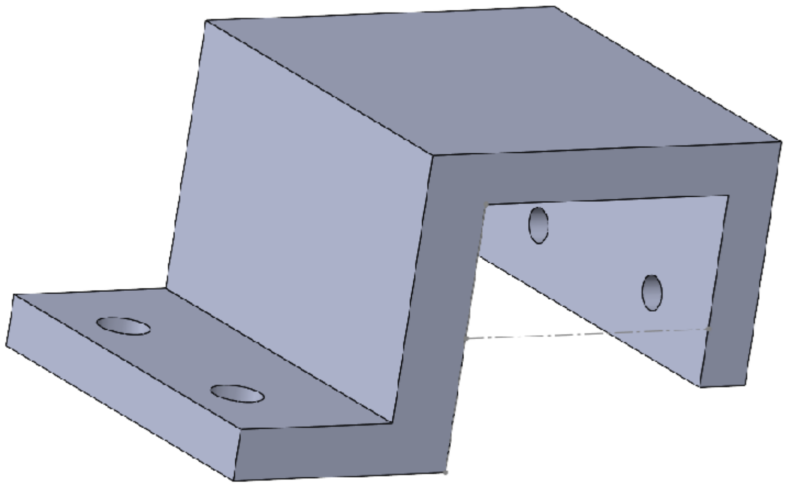

Figure 10: Connection to bulkhead

As discussed within the section dedicated to the plug the main mechanical connection point of the shock cords passes through the plug. With the material properties of PLA it was determined that it would be unable to handle the stresses applied and thus the aforementioned system was put in place. What was not mentioned then was the means of ensuring the plug did not rotate during its motion. This is primarily achieved by the lengthened sides of the plug maintaining contact with the inner diameter of the rocket body, thus preventing rotation. It should be mentioned that this does pose some risk of developing additional unwanted frictional forces, but these were determined to be negligible when compared to the force provided by the expanding CO_2 gas.

Figure 11: Shock Cord Connection Through Plug

Risk Assessment

A additional task undertaken to check the veracity of the design was to establish primary risks associated with it. In this case the below figure highlights the primary risks that can be anticipated under normal conditions or predictable abnormal conditions.

Risk	Consequences of Occurrence	Likelihood of Occurrence	Steps for Mitigation
Premature Explosive Decompression of CO2 Cannister	High	Low	Careful handling of cannisters before loading CO2 can only be deployed by Solenoid activation
Gas Vents Without Separating Rocket	High	Medium	Addition of rubber O ring to bulkhead Potential pre-launch pressure checks Majority of fasteners do not Pass through entirety of bulkhead, allowing for better sealing
Actuator Fails to Penetrate CO2 Cannister Seal	Medium	Low	Redundant secondary system Utilized actuators are selected to have sufficient application force, and are supplied with more than enough power by the battery system
Battery is Dead	Medium	Low	Pre-launch checks Redundant secondary system
Vibrations During Flight Cause Premature CO2 Cannister Firing	High	Low	Mounting using clip and rubber cement dampens vibrations Solenoid System only capable of activating with current

Figure 12: Risks Chart

It should be noted that the likelihood of different events is capable of changing based on environmental conditions. For example. The first condition of risk of explosive decompression of the cannisters is mostly associated with improper handling of the CO2 storage units. However, the risk changes based on the temperature in the local environment, as the pressure exerted on the cannisters by their contents will increase or decrease depending on the temperature. This means additional care should be taken in hotter climates to ensure accidents are averted.

Ch 3: Verification

Requirements (high level unless have verification for the low level ones)

Here are the requirements from the initial design proposal, may consider adding more later

Going into this project there were multiple major specifications that had to be taken into account for any designed system. These came from multiple sources, some straightforward in origin and some from competition specifications that the rocket team was subject to. Thus the list of initial requirements for this design are as follows:

1) System must be mechanical in nature

The main purpose of the Recovery sub team in seeking alternative designs was to break away from utilizing black powder charge cups as a method of deployment. Thus any designs that had similar issues would be deemed to be unacceptable. While the Recovery team continues to research alternative methods for black powder based deployment so as to avoid low pressure combustion issues, they desired a design that avoided the pitfalls of the substance in its entirety.

This requirement was met by utilizing CO2 gas, an substance incapable of harming the parachutes in the given circumstances.

2) The volume of the system must fit within current or future Akronauts rockets

Any system devised by this team was required to be able to fit within the internal bays of even the smallest of Akronauts rockets, in this case the 4-inch diameter rockets utilized for testing various systems.

This requirement was met with careful examination of the extension characteristics of the solenoid, and it should be noted that it only comes close to being an issue in the smallest of rockets.

3) System must have either internal or external redundancies to assure rocket separation

Due to the nature of parachute deployment and the resources available to the rocket team it is currently impossible to ascertain whether the system has correctly been deployed from the ground. As such any devised system was required to posses some methodology to assure deployment in case of any failure in the system.

This requirement was met utilizing a tried and tested method employed by the rocket team for years, implementing a parallel system with a equal or larger charge that is set off regardless of the first's deployment.

4) Mass must be minimized in order to assist in rocket performance

Akronauts Rocket Design Team is a organization that takes part in competitions, and thus it was undesirable that the system take available mass away from other sub-systems that may require it.

This was mostly met, however, there is always opportunity for further alterations to increase the mass efficiency of the system.

5) Design must be scalable

Due to the changing and developing nature of the rocket team it was important that the devised system not become a stumbling block for the team years down the line. As such the system was required to be utilizable by rockets of a variety of dimensions and force requirements.

The meeting of this requirement has already been mentioned in previous sections, but it is primarily met utilizing the ability to scale the size of the CO2 cannisters used. With this functionality the system can be used by any rocket that requires a charge covered by cannisters sized 30 g to 90 g.

6) The system must be resilient to vibrations

Launching a rocket involves significant vibrations during takeoff, thus the designed system must be capable of operating after being exposed to these forces.

This requirement is mainly met using connection methods and part orientation. The main reason for concern with vibration is to prevent premature or accidental deployment of the system, which is prevented utilizing the horizontal solenoid orientation, as well as the inbuilt spring mechanism.

7) The system must be securable to the bulkhead of a rocket section

Due to the location of the drogue parachute bay, there is little volume to spare in either the parachute bay or the neighboring electronics bay. As such the designed system should be capable of at least having part of its components secured to the bulkhead in an effort to save volume.

All parts are designed to be securable to the bulkhead by way of multiple methods.

Data

Solid data for the project is unfortunately lacking as of this report. The mainstay of data that has been gathered is in regard to calculated projections instead of gathered results and thus is thus not truly tested in actual environmental conditions.

What has been able to be accomplished is in regard to the anticipated pressure outputs of the system under various conditions, as well as estimating the minimum force able to be delivered by the wedge impactor. This allows for a better understanding of the scalability of the system and what cannisters will be necessary for future testing.

An estimation of the pressure delivered by the impactor at the lowest possible instance can be found utilizing basic pressure equations. Given that the solenoid used in this design can deliver 5 Newtons of force at the moment of full extension (a fact taken into account by the placement of the solenoid relative to the moment arm), this will act as the force value in the equation P=F/A. Assuming a rather dull point for the impactor at 1 mm^2 The pressure delivered by the system becomes $P = 5\ N/mm^2 = (5\ (kg\ m / s^2)/ (1\ mm^2))*((1000\ mm)^2 / (1\ m^2))$

Thus pressure applied to the seal assuming blunt 1 mm tip is $P = 5*10^6$ Pa

Process wise the calculations involved for determining the pressure provided by the CO2 are relatively simple. The process is as follows.

Firstly, establish the environmental conditions, in this case

R = 8.3144; J/mol*K

P = 101325 Pascals

T = 273.15 K

Next calculating how much CO2 is being utilized for a given calculation

Mm = 44 Molar Mass of CO_2

M = 90 USER INPUT MASS OF CO2 IN GRAMS

N = M/Mm Number of Mols of CO2

From there the volume that the CO2 will desire to expand to given these environmental conditions can be calculated.

V = (N*R*T)/P Volume of CO2 gas in STP

V_{CO2} = V*61024 converts meters cubed to inches cubed

Next the actual volume for the theoretical rocket can be calculated utilizing the volume equation $Vr = h * \pi * r^2$

Then by using the known volume and the volume the CO2 wishes to expand to, the resulting pressure can be calculated.

$P = (P_{env} * V_{CO2})/Vr$;

The first item to note is how the internal pressure of the CO2 changes based on the radius of the utilized rocket. While it is simple enough to state that venting into a larger volume will result in lower pressure it is important to note that this does not scale linearly. This is due to the use of circular rockets meaning that the volume equation is $Vol = h * \pi * r^2$. Due to this the pressure provided by the CO2 drops off rapidly. To counteract this it will be necessary for larger cannisters to be utilized for larger rockets, which is possible without modification in the range of 30g to 90g. The effects volume has on the pressure generated by cannisters in this range can be seen in the below figures x-y

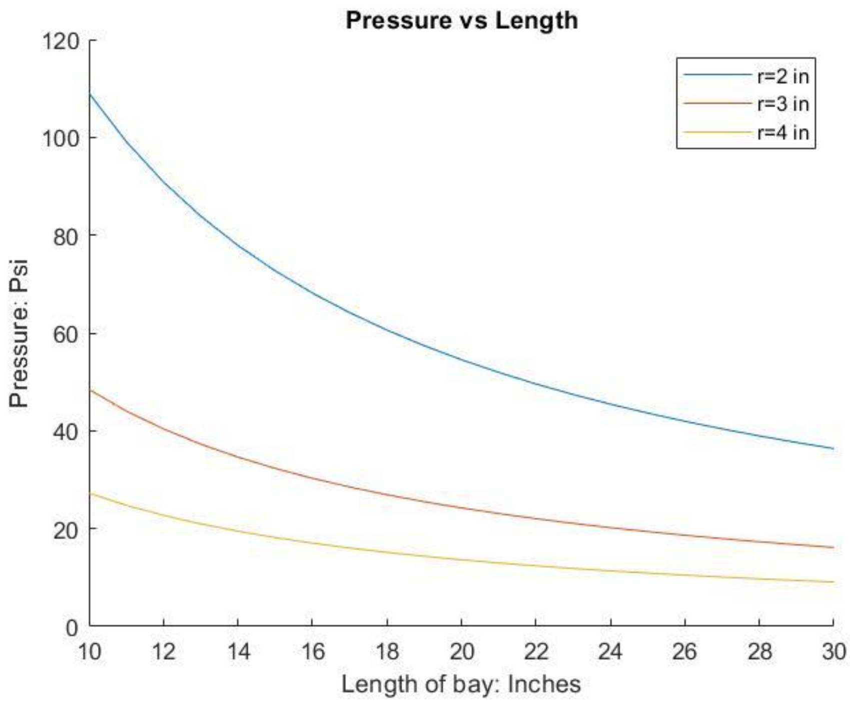

Figure 13: Display of Effects Radius has on Pressure for 30 grams CO2

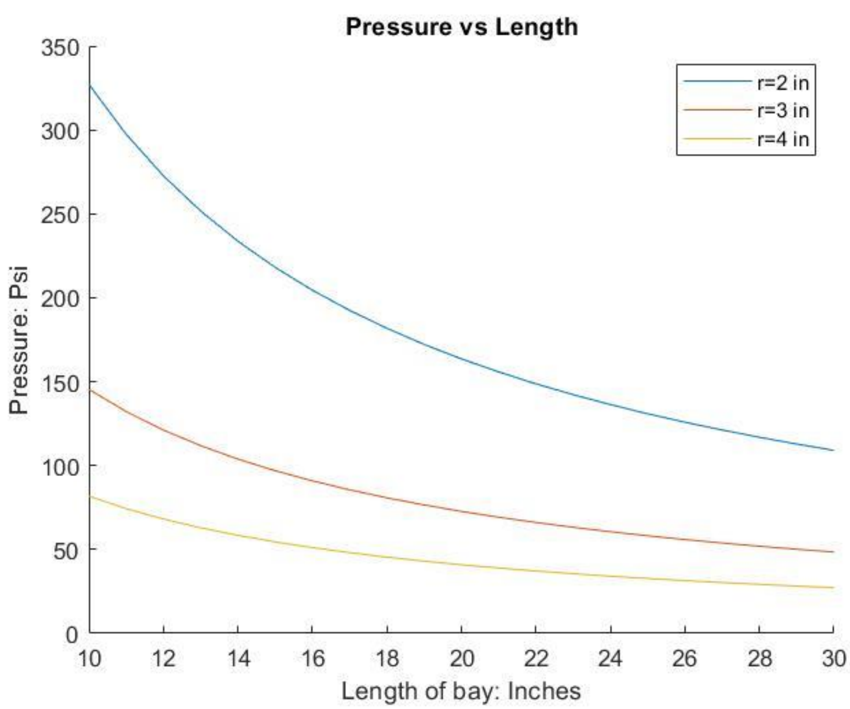

Figure 14: Display of Effects Radius has on Pressure for 60 grams CO2

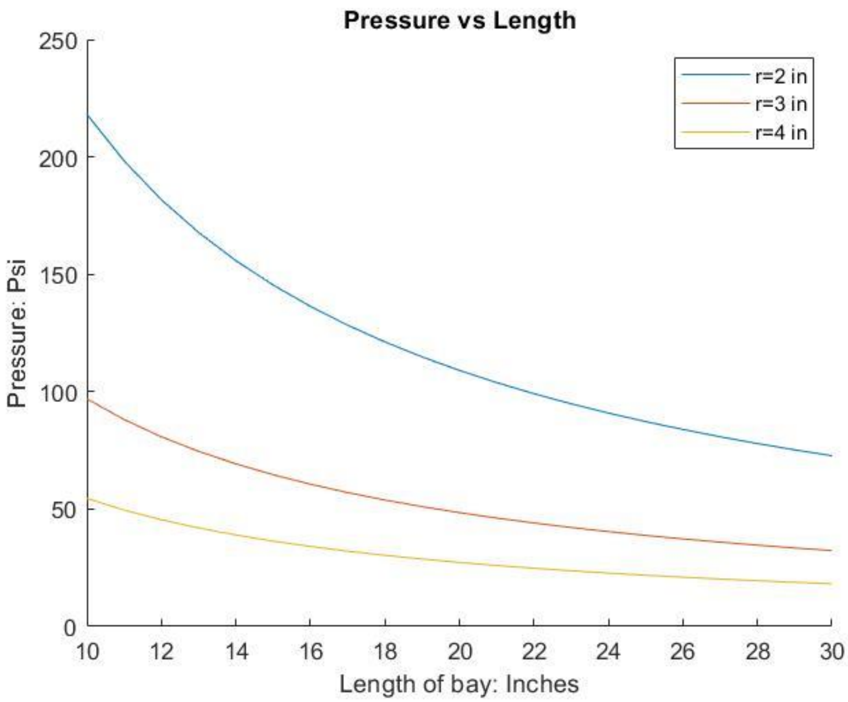

Figure 15: Display of Effects Radius has on Pressure for 90 grams CO2

This topic also brings with it the necessity to understand how the cannister sizes themselves effect the internal pressure. Keeping all other factors the same and assuming a sounding rocket radius of 2 inches, the resulting pressure generated by each can be demonstrated as below.

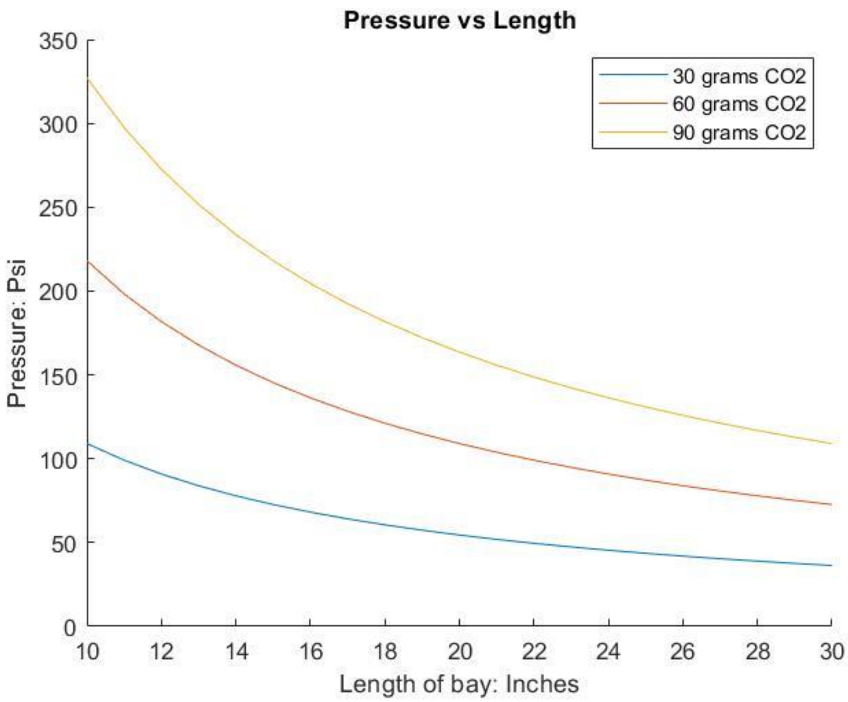

Figure 16: Display of Effects Different Cannister Sizes have on Pressure

Utilizing these techniques, the system is predicted to be able to generate sufficient force to overcome the sheer pins holding the recovery bay sections together with varying amounts of factor of safety. Examination of past black powder calculations utilized by the rocket team demonstrates a preferred factor of safety somewhere in the range of 3-4 times the force required to overcome the sheer pins. By using a similar factor of safety for a theoretical length drogue bay of 30 inches, it was determined that 60 grams, which generated 913.64 lbf would be necessary for such a bay. As demonstrated in the above plots this would be decreased with a shorter parachute bay. Thus, from these calculations it can be concluded that CO_2 under these conditions is a viable method for deployment.

Testing

Due to the project currently being in the design phase, there has been little testing able to be accomplished other than with the electronics. However, the recovery team does have established methodologies for verifying the functionality of systems prior to implementation. This typically takes the form of an ejection test, in which the structural sections of the rocket are fully assembled with a ready deployment system inside. The rocket is then suspended horizontally above the ground, so as to mimic the conditions of deployment as best as possible.

The only difference between the ejection system in this state and how it would be mounted for a launch has to do with the power supply wires, as instead of utalizing a flight computer it is simpler to simply attach the wires to a battery to complete the circuit and activate the system. Thus the wires pass out of the rocket, and then are connected to extension wires so this process can be performed some distance away. Since all systems currently employed by the rocket team employ current as the activation mechanism, this will also be the same for this design, as the actuation of the solenoid can be accomplished by simply connecting and disconnecting it from a power source.

Once the system is completely setup as described previously, the power source is connected to complete the circuit, and the system activated. The pass/fail criterion for this test is whether the system is able to overcome the shear pins holding the recovery bay together. It should be noted that unlike the actual use case, in which the primary and redundant systems are activated within a second of each other, the nature of human operators handling the wires necessitates that there be significant space between the primary and redundant systems being activated.

One thing that has become clear with past experimentation with CO_2 is the importance of maintaining the seals of the recovery bay where the gas is vented. During a test of the previously mentioned Raptor system, the CO_2 failed to overcome the shear pins using either the primary or the larger secondary charges. Upon review of the tests it was determined that the gas had vented out of a improperly sealed section of the body. This error likely came due to the difference between black powder and CO_2, where the black powder had sufficient impulse at sea level to provide enough force to overcome the shear pins before the venting became an issue. The findings of these experiments were a primary reason for the existence of the plug section of the design, as it became readily apparent that preventing gas venting as much as possible was important for this system.

Testing has also been determined as a location where there could be additional development work done. One thing that has been brough up with the Recovery sub team is the possibility of implementing pressure sensors inside the parachute bay during ejection testing. A series of ejection tests utilizing both CO2 and black powder would allow for better understanding of the difference between the impulse and pressure distributions of these two systems. This understanding could then be used to improve the design of both systems, and allow for superior functionality.

Costs

Of the costs associated with this project most of the come from personnel time investment. However, it is not wise to neglect the cost of materials and licenses involved. For instance, the main software used for calculating the internal pressure generated by different masses of CO2 for this project was MATLAB. This means that the university had to make Matlab licenses available for student use, thus assuming the university acquired these as permanent licenses at listed rates means that the MATLAB software alone used between two students cost $1000. Additionally, while most components of this design are capable of being 3d printed, certain parts such as the bulkhead and impactor were designed to be composed of machined metal. The smallest bulkhead would be a round section with diameter of 4 inches and thickness of 0.5 inches. Assuming that this is machined out of a square 4x4x0.5 inch aluminum the bulkhead has a cost of approximately $15.52 per part.

Other more upfront costs of this system are as follows:

Strato logger:

Solenoid Actuator: $11 per unit

Material Cost of PLA:

12 V Battery: $5-$15

Finally, the labor cost was by far the more significant sum in regards to this project. Utilizing the provided labor cost formula per individual of Salary * Hours Spent * 2.5 will allow for an estimation of this figure. Unfortunately no logs were taken of exact hours spent on this project, leaving only estimation to work with. As such, utilizing a estimation based on hours preparation on various segments (initial research, modeling, time spent in Recovery meetings coordinating, preparation of presentations of papers) the approximated hours spent on this project comes out to approximately 90 hours per individual. Likewise there was so set salary or hourly rate, and thus this must be estimated based on past and present experience. Assuming a hourly rate of $28 per hour, this allows for a complete calculation resulting in a personnel cost of $12600 between the two individuals involved in this project.

Ch 4: Conclusions

The process of this system's development was an interesting showcase in the difference between the straightforward design projects often assigned in classes and the more open-ended problems that may come up when working in a research and development environment, whether it be academic or industry. Firstly, the shear amount of time that must be spent establishing the foundation of a design before anything else can be done is something that is never properly illustrated in classroom projects. There the students are often provided with the relevant assumptions and tools they are expected to make use of, while in this project there was simply a problem, and the methodology used to solve it was a matter of selection and justification rather than right or wrong.

This design has to the best of its ability met the requirements set out in the verification section, but even they were things that had to be identified in order to progress. This design was one of many that were brainstormed, reviewed, discarded or altered depending on their apparent promise, and through that process was refined from vague sketches into a realized and manufacturable model that is now displayed. In addition to this, the design takes into account the margins of safety in order to ensure the CO_2 is sufficient to separate the sections reliably, and through that and other efforts attempts to make sure this design is as consistent in its function as possible.

References

Kendall, M.A.F., Quinlan, N.J., Thorpe, S.J. *et al.* Measurements of the gas and particle flow within a converging-diverging nozzle for high speed powdered vaccine and drug delivery. *Exp Fluids* **37,** 128–136 (2004). https://doi.org/10.1007/s00348-004-0792-4

This reference is primarily as a demonstration of gas flow modeling for breached gas cannisters.

Pepermans, Lars & Menting, Esmée & Rozemeijer, Mark & Koops, Bram & Khurana, Sayyam & van Marion, Francesca & Kuhnert, Felix & Serman, Matteo & Stebbins Dahl, Nathaniel & Suard, Noah. (2019). Comparison of Various Parachute Deployment Systems for Full Rocket Recovery of Sounding Rockets.

Paper demonstrating some concepts of rocket recovery system design.

Oosthuizen Patrick, Carscallen William, Introduction to Compressible Fluid Flow, CRC Press 711 Third Avenue New York NY, 2014

Textbook illustrating compressible flow and a source for atmospheric conditions

White, Kevin J. Sasse, Ronald A. RELATIONSHIP OF COMBUSTION CHARACTERISTICS AND PHYSICAL PROPERTIES OF BLACK POWDER, US Army Armament Research and Development Command, November 1982

Matlab Code Utilized for Calculations

```
%senior design project Nicholas Anthony

%CO2 pressure calculations

%This matlab code calculates standard temperature and pressure of volume of

%CO2 given the liquid mass of CO2

clc
```

```
clear

close all


R = 8.3144; %J/mol*K

P = 101325; %Pressure in Pascals

T = 273.15; %Temperature in degrees kelvin

Mm = 44; %Molar Mass of CO2


M = 30; %USER INPUT MASS OF CO2 IN GRAMS******


N = M/Mm; %N = Number of Mols of CO2


V = (N*R*T)/P; %Volume of CO2 gas in STP (Meters^3)(101325 Pascals or 1 ATM, 0 Degrees Celcius or 273.15 Degrees Kelvin)

Vin = V*61024; %converts meters cubed to inches cubed

r1 = 2; %radius of bay tube measured in inches (USER INPUT)******

r2 = 3;

r3 = 4;

    xlabel("Length of bay: Inches")

    ylabel("Pressure: Psi")

h = 10:30 %height of recovery bay (USER INPUT - FROM BULKHEAD TO BULKHEAD * ENSURE THIS IS THE HEIGHT OF THE ENTIRE BAY)*****

A1 = pi*r1^2 %Area of bulkhead used to calculate volume of the recovery bay
```

```
A2 = pi*r2^2

A3 = pi*r3^2

BV1 = A1*h; %Calculates volume of the recovery bay at r=2

BV2 = A2*h; %Calculates volume of the recovery bay at r=3

BV3 = A3*h; %Calculates volume of the recovery bay at r=4

p1 = (P*Vin)./BV1; %calculates the internal pressure of the recovery bay (IN PASCALS) at r=2

p2 = (P*Vin)./BV2; %calculates the internal pressure of the recovery bay (IN PASCALS) at r=3

p3 = (P*Vin)./BV3; %calculates the internal pressure of the recovery bay (IN PASCALS) at r=4

pin1 = p1/6895; %converts pressure from pascals to psi

pin2 = p2/6895;

pin3 = p3/6895;

hold on

F1 = pin1*A1 %calculates the force on ejection puck (Force in LBS)

F2 = pin2*A2

F3 = pin3*A3

plot(h,pin1)

plot(h,pin2)

plot(h,pin3)

title('Pressure vs Length')

legend("r=2 in", "r=3 in", "r=4 in")


figure(2)
```

```
M1 = 30; %USER INPUT MASS OF CO2 IN GRAMS******

M2 = 60; %USER INPUT MASS OF CO2 IN GRAMS******

M3 = 90; %USER INPUT MASS OF CO2 IN GRAMS******

N1 = M1/Mm; %N = Number of Mols of CO2

N2 = M2/Mm; %N = Number of Mols of CO2

N3 = M3/Mm; %N = Number of Mols of CO2

V1 = (N1*R*T)/P; %Volume of CO2 gas in STP (Meters^3)(101325 Pascals or 1 ATM, 0
Degrees Celcius or 273.15 Degrees Kelvin)

V2 = (N2*R*T)/P;

V3 = (N3*R*T)/P;

Vin1 = V1*61024; %converts meters cubed to inches cubed

Vin2 = V2*61024;

Vin3 = V3*61024;


r1 = 2; %radius of bay tube measured in inches (USER INPUT)******



    xlabel("Length of bay: Inches")

    ylabel("Pressure: Psi")

h = 10:30 %height of recovery bay (USER INPUT - FROM BULKHEAD TO BULKHEAD *
ENSURE THIS IS THE HEIGHT OF THE ENTIRE BAY)*****

A1 = pi*r1^2 %Area of bulkhead used to calculate volume of the recovery bay
```

```
BV1 = A1*h; %Calculates volume of the recovery bay at r=2



p1 = (P*Vin1)./BV1; %calculates the internal pressure of the recovery bay (IN PASCALS)

p2 = (P*Vin2)./BV1;

p3 = (P*Vin3)./BV1;

pin1 = p1/6895; %converts pressure from pascals to psi

pin2 = p2/6895;

pin3 = p3/6895;

hold on

F1 = pin1*A1 %calculates the force on ejection puck (Force in LBS)


plot(h,pin1)

plot(h,pin2)

plot(h,pin3)

title('Pressure vs Length')

legend("30 grams CO2", "60 grams CO2", "90 grams CO2")

hold off
```