Low Shock Payload Separation System

Background Report

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1 Background

Orbital ATK, a global leader in aerospace and defense technologies, builds and delivers space systems ranging from satellites to military defense systems. Their main products include launch vehicles and satellites. Orbital ATK was created when two companies, Orbital Sciences Corporation and ATK, merged to form Orbital ATK, employing approximately 12,000 employees worldwide [1]. Orbital ATK is divided into three main operating groups: Flight Systems Group, Defense Systems Group, and Space Systems Group [1]. This project focuses on Orbital ATK's three main launch vehicles: Antares, Pegasus, and Minotaur [2].

1.1 Introduction

Currently, Orbital ATK purchases their low-shock payload separation systems from other companies. As there are many different systems on the market, the availability is not the problem. Our client would like to bring the production of these systems in-house in order to save money and have more control over the production process. This plan addresses the contemporary issue of manufacturing outsourcing. Orbital ATK has an ultimate goal of vertically integrating their company.

1.2 Project Description

Orbital ATK has commissioned this capstone team to design a low-shock payload separation system that can be built in-house at a fraction of the cost compared to what their competitors manufacture. Orbital ATK has provided us with the following goals:

[1] Work with Orbital ATK mechanical engineers to understand the needs and desires of the delivered project;
[2] Survey commercially available separation systems;
[3] Develop design concepts that meet all requirements;
[4] Perform trade studies to down select to a single design;
[5] Manufacture a prototype; and
[6] Provide Orbital ATK with PDR and CDR presentation.

The final product will include design, analysis and a manufactured prototype.

1.3 Original System

The three main launch vehicles, Antares, Pegasus, and Minotaur, are explained more in depth in section 3 of this paper. This team is designing a low impact separation mechanism. This team compared 4 different separation systems: Orbital ATK's 38" separation system, RUAG PAS 381S, Planetary Systems Corporation Motorized Lightband, and the NanoRack separation system. The structure, operation, performance, benefits, and deficiencies are explained in detail in section 3.

2 Requirements

Orbital ATK has given our team a set of customer requirements discussed in section 2.1. The customer requirements were given weights based on how important they were to the customer. Engineering requirements, discussed in section 2.2, were then determined based on the customer requirements and given quantifiable values as goals for the design of our system.

2.1 Customer Requirements

In an effort to find which performance characteristics would receive the most attention during the design process, each customer requirement was assigned a value from 0 to 5 based on their level of importance.

Table 1: Customer Requirements

Customer Requirements	Weighting	Justification
Low Shock	5	One of the main objectives of this project requires that we create a system that will not impart excessive amounts of vibration to the payload being released. As such, low shock has been given a high priority and will be one of the main focuses throughout the project.
Low relative cost	4	Orbital ATK's motivation for creating their own low shock payload separation system includes saving money, and because of this, the cost of the system must be kept to a minimum.
In-House manufacturability	3	Orbital needs to be able to manufacture the chosen design at their facility. However, Orbital ATK has many manufacturing resources available to their use. As such, it has been given a lower priority.
Compatible with existing payload systems	5	Compatibility has been given a weight of 5. The chosen design must be able to function with existing systems. Due to this face, a high priority has been given to compatibility.
No debris upon separation	2	Debris upon separation, while important, allows for an easy design alteration, and because of this debris has been given a low priority.
Withstand stresses during flight	5	As low shock is the goal, the ability of our design to withstand the forces encountered during flight directly relates to the success of the separation system.
Electrical pulse to Signal Separation	3	The signal to initiate separation, as outlined by the client, requires an electrical pulse. This requirement has been given a medium priority because most systems benchmarked are actuated electrically, meaning that the initial signal would be electric.

2.2 Engineering Requirements

The engineering requirements, drawn from our customer requirements, give quantifiable values as targets for the performance of our design. Given in the table below, are the requirements and their respective tolerances.

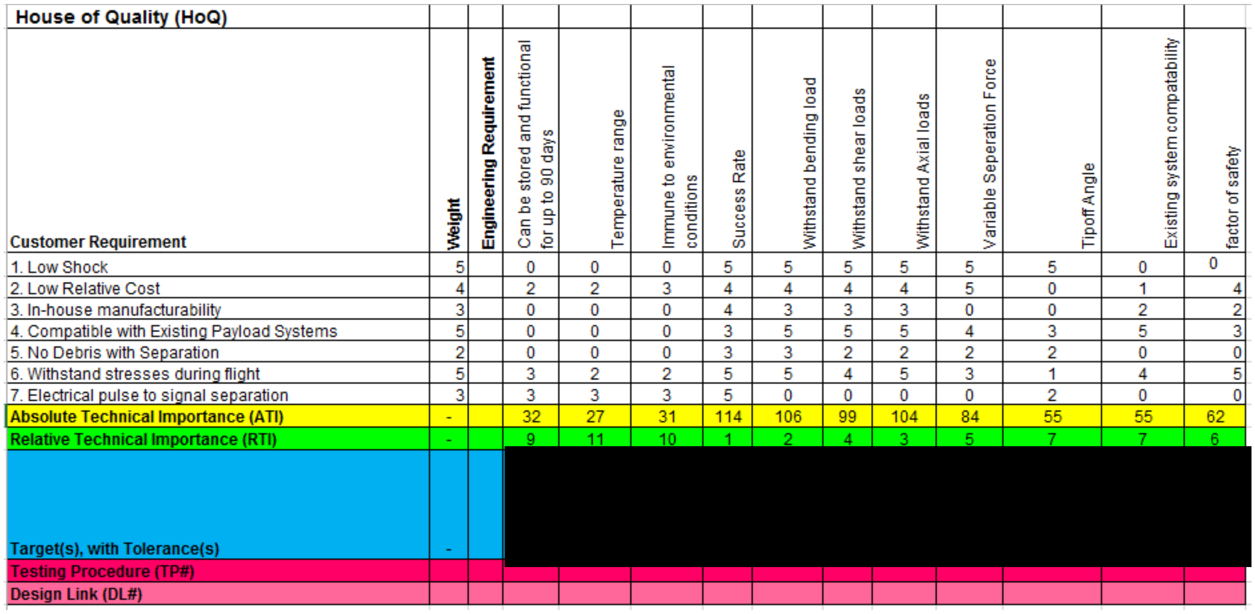
Table 2: Engineering Requirements

Engineering Requirements	Target/Tolerance	Rational
Can be stored and functional for up to 90 days	[redacted]	This requirement is to allow for the separation system to be used if the original launch is delayed.
Temperature range	[redacted]	From the problem statement we were given, this was the minimum and the maximum expected range of temperatures that the separation system is going to reach.
Immune to environmental conditions	[redacted]	Immunity to environmental conditions is to ensure that the system will not rust when it is in stored in a container.
Success rate	[redacted]	The desired success rate was determined through the benchmarking of comparable systems.
Withstand bending load	[redacted]	This requirement was given by the client to show the expected bending load
Withstand shear loads	[redacted]	This requirement was given by the client to show the expected shear loads.
Withstand axial loads	[redacted]	This requirement was given by the client to show the expected Axial loads.
Variable separation force	[redacted]	The Variable Separation Force is required by the client so they can change the force separating the systems depending on the payload
Tipoff angle	[redacted]	Tip-off angle is the rate at which the center-of-gravity of the payload rotates upon separation. Our goal is to keep it to a minimum.
Existing system compatibility	[redacted]	This is to ensure that the systems will be able to be used by the client for its intended use.
Factor of safety	[redacted]	This is to ensure that the payload will not break by the forces it experiences when being launched.

2.3 House of quality (HoQ)

This team has organized the customer requirements and the engineering requirements into a House of Quality in order to evaluate the absolute technical importance (ATI) and the relative technical importance (RTI). The ATI assigns a numerical importance value based off of how each engineering requirement affects or contributes to each individual customer requirement. The RTI simplifies these numbers and chronologically orders each need to signify the sequential importance.

Table 3: House of Quality



House of Quality (HoQ)													
Customer Requirement	**Weight**	**Engineering Requirement**	Can be stored and functional for up to 90 days	Temperature range	Immune to environmental conditions	Success Rate	Withstand bending load	Withstand shear loads	Withstand Axial loads	Variable Seperation Force	Tipoff Angle	Existing system compatability	factor of safety
1. Low Shock	5		0	0	0	5	5	5	5	5	5	0	0
2. Low Relative Cost	4		2	2	3	4	4	4	4	5	0	1	4
3. In-house manufacturability	3		0	0	0	4	3	3	3	0	0	2	2
4. Compatible with Existing Payload Systems	5		0	0	0	3	5	5	5	4	3	5	3
5. No Debris with Separation	2		0	0	0	3	3	2	2	2	2	0	0
6. Withstand stresses during flight	5		3	2	2	5	5	4	5	3	1	4	5
7. Electrical pulse to signal separation	3		3	3	3	5	0	0	0	0	2	0	0
Absolute Technical Importance (ATI)	-		32	27	31	114	106	99	104	84	55	55	62
Relative Technical Importance (RTI)	-		9	11	10	1	2	4	3	5	7	7	6
Target(s), with Tolerance(s)	-		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Testing Procedure (TP#)													
Design Link (DL#)													

3 Existing Designs

This capstone team has identified three launch vehicles that could implement our designed separation mechanism: Antares, Pegasus, and Minotaur [2].

3.1 Design Research

Design research was conducted using predominantly online resources, supplemented with information provided by our client contact. Exact performance characteristics are difficult to obtain given the competitive nature of the aerospace industry, however, any relevant information that could be obtained is presented in sections 3.2-3.3.

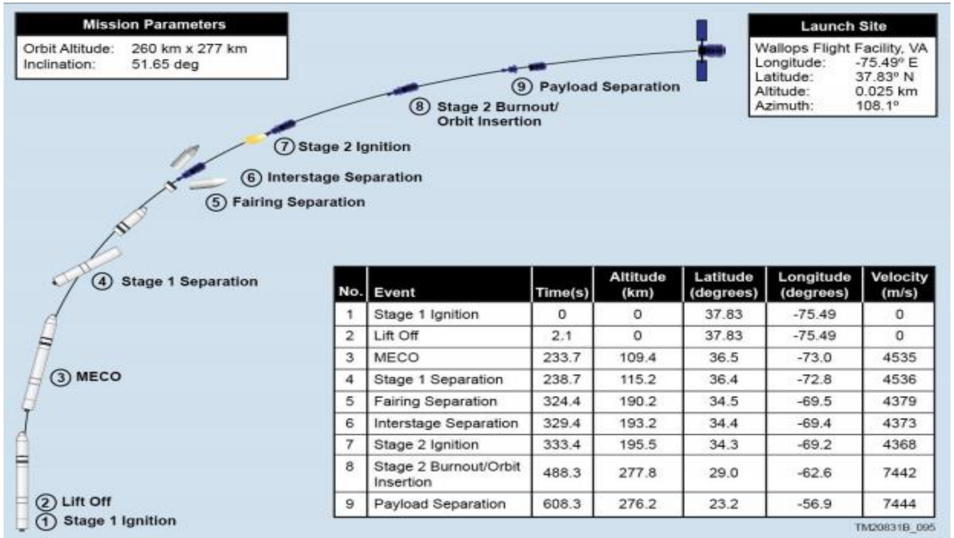
3.2 System level

Orbital ATK has three main launch vehicles. Two are for any company that needs to send up a small-medium sized payload. The third is strictly for government use. Figure 1 shows (from left to right) the Antares, Pegasus, and Minotaur Launch Vehicles [2].

Figure 1: Antares, Pegasus, and Minotaur Launch Vehicles, respectively [2]

3.2.1 Existing Design 1: Antares

The Antares was designed to resupply the International Space Station (ISS) but has also been used in commercial, scientific, and defense applications [3]. There have been 5 total launches since April 2013 with 1 recordable failure [4]. Figure 2 shows the breakdown of how each component of the rocket separates during ascension into orbit [5].



Mission Parameters

Orbit Altitude:	260 km x 277 km
Inclination:	51.65 deg

Launch Site

Wallops Flight Facility, VA

Longitude:	-75.49° E
Latitude:	37.83° N
Altitude:	0.025 km
Azimuth:	108.1°

No.	Event	Time(s)	Altitude (km)	Latitude (degrees)	Longitude (degrees)	Velocity (m/s)
1	Stage 1 Ignition	0	0	37.83	-75.49	0
2	Lift Off	2.1	0	37.83	-75.49	0
3	MECO	233.7	109.4	36.5	-73.0	4535
4	Stage 1 Separation	238.7	115.2	36.4	-72.8	4536
5	Fairing Separation	324.4	190.2	34.5	-69.5	4379
6	Interstage Separation	329.4	193.2	34.4	-69.4	4373
7	Stage 2 Ignition	333.4	195.5	34.3	-69.2	4368
8	Stage 2 Burnout/Orbit Insertion	488.3	277.8	29.0	-62.6	7442
9	Payload Separation	608.3	276.2	23.2	-56.9	7444

Figure 2: Antares Separation Process [5]

The Antares is a two-stage rocket used to send medium payloads weighing 7,000-9,000 kilograms into orbit. It is 9.9 meters long by 3.9 meters in diameter, and weighs 290,000 kilograms [5]. Major components include the avionics assembly, Aerojet engines, payload fairing, payload interface system, and separation system [3].

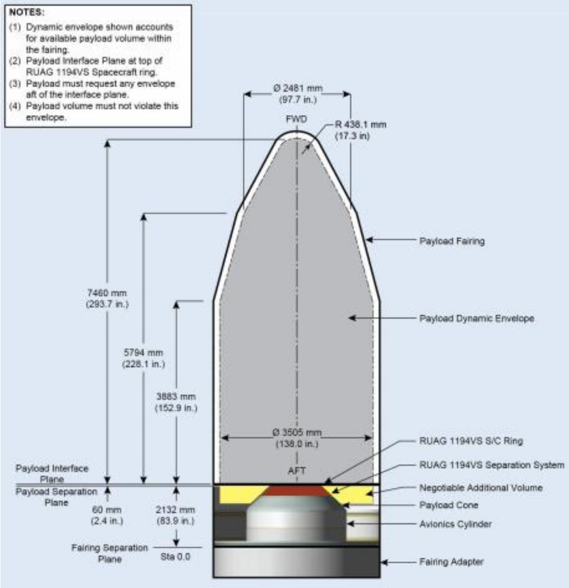


Figure 3 Antares Vehicle [5]

A standard 62-inch bolted payload cone offers a wide variety of separation systems to be integrated into the vehicle. The most popular used for the Antares is the RUAG Marmon Clamp Separation System. Figure 3 illustrates where each component is on the launch vehicle [5].

3.2.2 Existing Design 2: Pegasus

In 1989, Orbital unveiled the Pegasus. This was Orbital's first commercially developed launch vehicle, providing an opportunity for companies to send their payloads into orbit. This is the only launch vehicle this company has that is launched horizontally using a carrier aircraft [6]. There have been 42 total launches with 3 recorded failures [7]. Figure 4 shows how the rocket separates during each stage while launching into orbit [8].

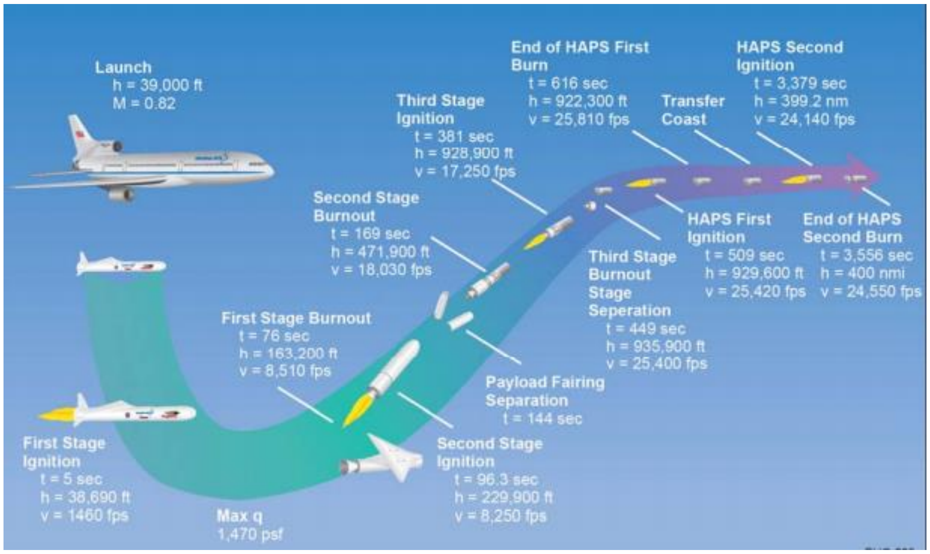


Figure 4: Pegasus Separation Process [8]

The Pegasus is a three-stage rocket weighing 23,000 kilograms. It is 17 meters long with a diameter of 1.5 meters. It can carry payloads of up to 450 kilograms into low Earth orbit [8]. The Pegasus has nine crucial components: avionics assembly, lifting wing, aft skirt, payload fairing, payload interface system, three motors, and the separation system [6].

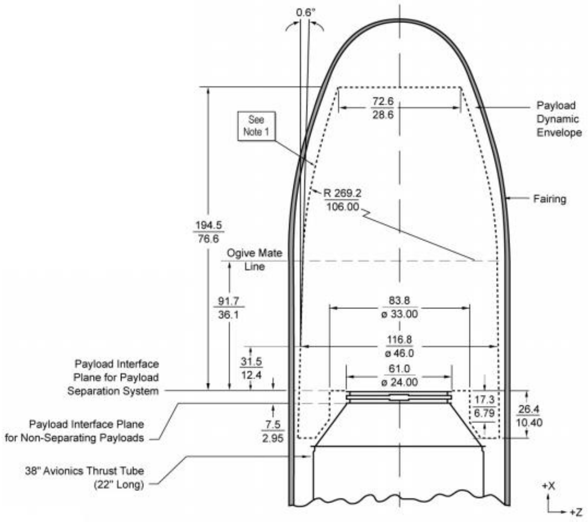
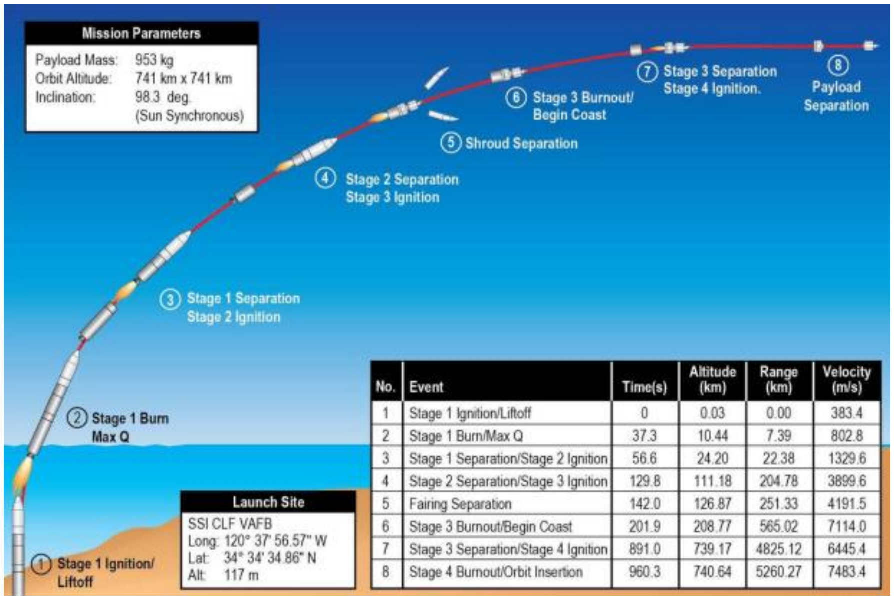


Figure 5: Pegasus Vehicle [8]

The Pegasus uses two different separation systems; one is 97 cm while the other is 56 cm in diameter. Orbital ATK manufactures both systems in-house. Figure 5 illustrates where each component is on the launch vehicle [8].

3.2.3 Existing Design 3: Minotaur

The Minotaur family consists of six different rockets and is exclusively used by the United States Government [9]. The Minotaur, starting in 2001, has completed 25 missions with a success rate of 100% [10]. Figure 6 shows the breakdown of how each component of the rocket separates while launching into orbit [11].



Mission Parameters

Payload Mass: 953 kg
Orbit Altitude: 741 km x 741 km
Inclination: 98.3 deg. (Sun Synchronous)

Launch Site

SSI CLF VAFB
Long: 120° 37' 56.57" W
Lat: 34° 34' 34.86" N
Alt: 117 m

No.	Event	Time(s)	Altitude (km)	Range (km)	Velocity (m/s)
1	Stage 1 Ignition/Liftoff	0	0.03	0.00	383.4
2	Stage 1 Burn/Max Q	37.3	10.44	7.39	802.8
3	Stage 1 Separation/Stage 2 Ignition	56.6	24.20	22.38	1329.6
4	Stage 2 Separation/Stage 3 Ignition	129.8	111.18	204.78	3899.6
5	Fairing Separation	142.0	126.87	251.33	4191.5
6	Stage 3 Burnout/Begin Coast	201.9	208.77	565.02	7114.0
7	Stage 3 Separation/Stage 4 Ignition	891.0	739.17	4825.12	6445.4
8	Stage 4 Burnout/Orbit Insertion	960.3	740.64	5260.27	7483.4

Figure 6: Minotaur Separation Process [11]

As the designs of the family progressed, they got larger; the Minotaur I is the smallest and the Minotaur VI is the largest. The Minotaur family is capable of launching payloads weighing up to 3,000 kilograms [11]. Major components include the avionics structure, payload adapter cone, motors, motor adapter cone, payload fairing, and separation system [9].

3.3 Subsystem Level

This capstone team researched and evaluated a current subsystem used by Orbital ATK and three subsystems designed and manufactured by competitors. The subsystems evaluated are the Orbital ATK 38-inch separation system, the RUAG PAS 381S, the Planetary Systems Corporation Motorized Lightband, and the NanoRacks separation system. To further breakdown the systems that the team researched, a hierarchy functional decomposition was constructed to help understand the key functions of a separation system as provide below.

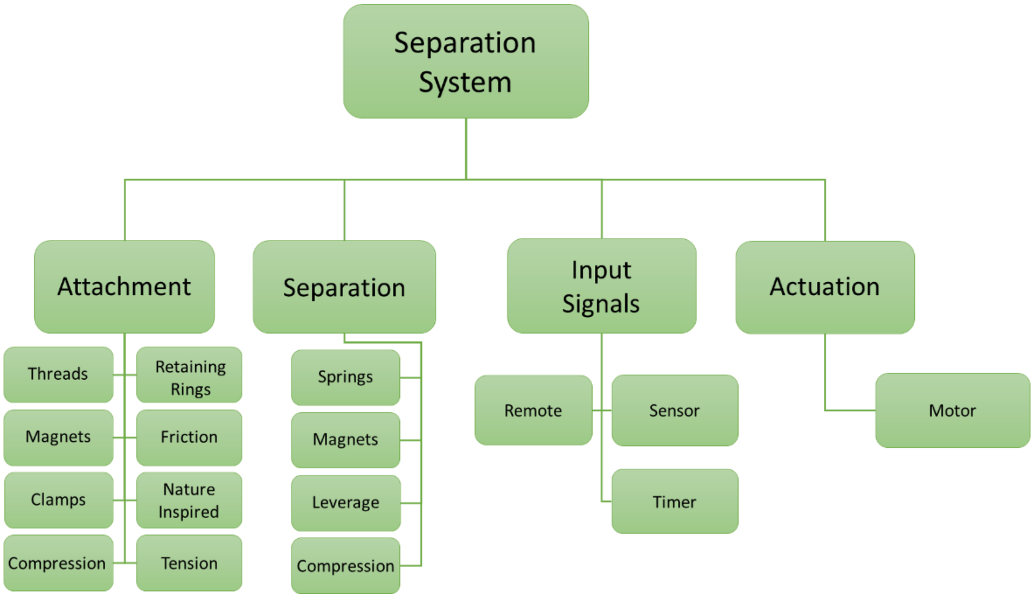


Figure 7: Hierarchy Functional Decomposition

The four main functions of a separation system are attachment, separation, incoming signals, and actuation. Once the team figured out what the key functions were of these systems, the team theorized methods to perform the four functions. For example, for attachment threads, magnets and friction some methods of attachment that could be used. As for the incoming signals, this branch was looking at the different methods at which the separation system will be able to take in information of the flight mission and know when to initiate the separation procedure.

3.3.1 Original Subsystem: Orbital ATK

In researching for our project and upon the request of our client, we researched the companies whose products are similar to that which we set out to design. In our research, we came across Orbital ATK's own records and found their system. The Orbital ATK 38-inch separation system was designed for lighter payloads. The main separation system required the system to break the restraint for the payload to jettison.

3.3.1.1 Orbital ATK 38" Separation System Structure and Operation

Orbital ATK's 38" separation system is a single stage, two-part system that uses a V-band clamp, also known as a Marman clamp, to secure the payload and the launch vehicle rings together [9]. In order for the system to initiate its separation process, two bolt cutters would cut the V-band clamp in two places allowing the payload to separation from the launch vehicle [9]. The cut V-band sections would be caught in catches to reduce fly away debris from the system [9]. Figure 8 below shows a side view of Orbital ATK's system.

Figure 8: Orbital ATK 38" Separation System [9]

3.3.1.2 Orbital ATK 38” Separation System Performance and Benefits

As of August 2015, this system has flown in over 40 successful flight missions [9]. Our client pointed out three advantages to this design when the team inquired about the system, two of which being simplicity and reliability. In-house manufacturability is the main advantage to this design. However, with benefits come drawbacks.

3.3.1.3 Orbital ATK 38” Separation System Deficiencies

The Orbital ATK 38” separation system is having deficiencies that came with the system construction and operation. During a meeting with our client, head mechanical engineer Steven Hengl, about their company's system two main deficiencies were pointed out. First, the system is heavy compared to other systems added additional strain on the launch vehicle compared to their competitors’. The goal for these systems is to have minimal shock generated during the separation process. Next, Orbital ATK’s system generates high amounts of shock during the separation because of the bolt cutter cutting through the restraining clamp holding the two rings together. With this new knowledge, we began research into other companies’ separation systems that are generate little to no shock.

3.3.2 Subsystem 1: RUAG

The first system that drew the attention of the team was the separation system from RUAG. From the systems we researched, a reoccurring trend was appearing. RUAG fits in this trend by using a V-band clamp to secure the payload. The V-band clamp commonly is a flexible metal band with a V shaped notched where the two parts of the system are secured together.

3.3.2.1 RUAG PAS 381S Structure and Operation

The RUAG PAS 381S 15-inch single stage, two-part module separation system that uses a V-band clamp to hold a payload ring to a main vessel ring [12]. Once the vessel reaches the optimal separation height the system initiates. The motor loosens a circular lightband holding the payload ring and the hub ring together. Once the lightband is loosened for the payload to separate, springs at strategic positions on the hub ring push the payload away from the vessel thus, completing the separation. In 2012, the ring structure underwent refinement to reduce critical stress zone on the clamp and the rings [13]. As presented below in figure 8, a slight riser was added in the construction of the contact locations of the rings to reduce rotation and lateral movement prior to the systems separation [13].

Figure 9: PAS 381S by RUAG [12]

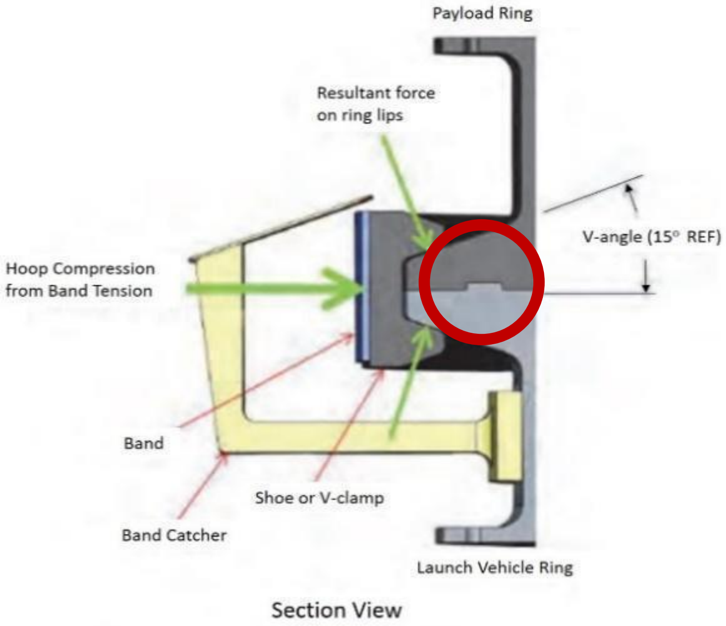


Figure 10: RUAG Modification [13]

3.3.2.2 RUAG PAS 381S Performance

According the RUAG, throughout this system's operation it has been used in 550 in-orbit separation. Of those, the system has had a success rate of 100% [13].

3.3.3 Subsystem 2: Planetary Systems Corporation

The second system that was analyzed is a system from Planetary Systems Corporation (PSC). This system is called the Planetary Systems Corporation Motorized Lightband and is represented in figure 9. This also fits the trend of using a marman clamp to secure the payload to the launch vehicle and similar in structure as the RUAG system; however, there is one difference.

3.3.3.1 PSC Motorized Lightband Structure and Operation

The Mark II Motorized Lightband (figure 9) is a single stage, two-part assembly that utilizes a V-band clamp similar to the PAS 381S; however, Planetary Systems Corporation refined the design to reduce the chance of debris upon separation. PSC inverted the V-band clamp so the clamp is on the inside of the system, increasing controllability of the ring upon separation [14]. The Mark II operates in the same manner, but instead of loosening the clamp the Mark II tightens the V-band clamp releasing the payload from the vessel [14]. Upon further research, no information was found about any subsequent refinements to this system.

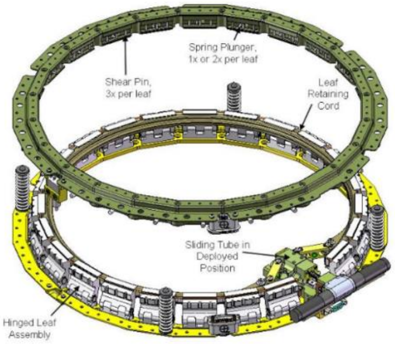


Figure 11: Mark II Motorized Lightband by Planetary Systems Corporation [14]

3.3.3.2 PSC Motorized Lightband Performance

According to the records of Planetary Systems Corporations out of 45 flights, this system has a success rate of 100% [14].

3.3.4 Subsystem #3: NanoRacks Separation Systems

The third system our team researched is called NanoRacks Separation System (NRSS). This system does not have V-band clamp in its system; however, even though this system does not have a V-band clamp and is currently in use on the International Space Station (ISS) there are still systems that the team feels could prove useful for our system.

3.3.4.1 NanoRacks Separation Systems Structure and Operation

As represented in the figure 10, similar to the PAS 381S and the Mark II, the NRSS is a two-part separation system where one half remains with the payload after the separation. The key difference the NRSS has from the Mark II and the PAS 381S is the use of separation switches over the V-band clamp [15]. The NRSS has three sets of three springs that are compressed when the payload ring is attached to the launch platform

[15]. When the separation switches are triggered the payload will release from the launch platform allowing the springs to stretch out, pushing the payload was away.

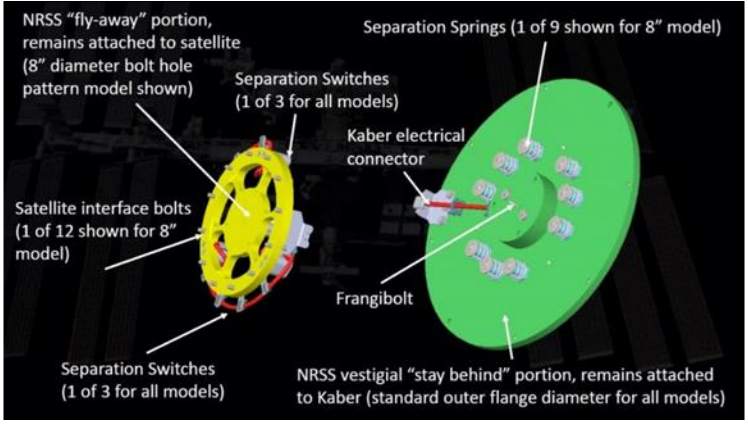


Figure 12: NanoRacks Separation System [15]

3.3.4.2 NanoRacks Separation Systems Performance

Since this was, implement last year no data of the success of the system has been released to the public.

4 Designs Considered

Going into the decision-making process the team started with ten designs, three of which were bio-inspired designs that incorporated mechanisms used in nature to help address the challenges posed by low-shock separation in space. The technical criterion with which these designs were compared to are outlined in customer and engineering requirements. Decisions were made based on how the team felt the concept would perform compared to the technical criterion. Some concepts were also incorporated into later designs to create hybrid designs that could perform better than the initial concepts that lead to the development of the hybrid design.

4.1 Bio-Inspired: Riffle Beetle legs

Riffle beetle legs are used as a model of how nature clamps onto things. The legs of riffle beetles hold onto underwater substrates in fast currents using their large, strong terminal claws. The concept of how the Riffle Beetle clamps onto underwater substrates is incorporated into the J-clamp design. See figure A1 in Appendix A.

4.2 Bio-inspired: Plant Tendrils

The cucumber plant tendrils twist due to an asymmetric contraction of an internal fiber specialized cell. Spring action, like the cucumber plant tendrils, is used in both the bolt design and the Polymagnet design. See figure A2 in Appendix A.

4.3 Bio-inspired Design: Jawless Mouth of the Lamprey

In early design concepts the idea of suction as a means of securing the two halves of the separation mechanism was discussed as a possible way to assure attachment during ascension, but was ultimately discarded because the team was not sure if suction would work in the vacuum of space. See figure A3 in Appendix A.

4.4 Interlocking Clamp system

The interlocking clamp design uses a series of clamps mounted radially on the inside of the launch vehicle side of the system. During ascent, the clamps will be locked onto the payload side of the system to ensure that the payload stays secured during launch and ascension. Upon separation, the clamps are pulled away from their locked positions using cables attached to each clamp. Springs would then take over to push the payload away from the launch vehicle in a controlled manner. The advantages to this system are that the clamps would provide ample force to secure the load, also, this design is similar to another system that has already been implemented with some success. The disadvantage to this system is that, the clamps require some force to keep them engaged during ascent, this becomes problematic when considering the energy required to keep the system engaged, as energy, in the form of electricity, is a scarce commodity on a launch vehicle. See figure A4 in Appendix A.

4.5 Press Band System

The press band system uses an adjustable band on the inside circumference of the launch vehicle payload that slots into a ring attached to the payload side of the system. During ascent, the ring is forced out to secure the top ring to the bottom ring. During separation, the ring is contracted allowing the payload ring to slide off the launch vehicle ring. After contraction of the ring, springs take over to provide the force to push the payload away from the launch vehicle. The advantage to this system is the simplicity of having the ring being the only moving part. One disadvantage is that it would be hard to ensure that the payload wouldn’t tip off during separation. See figure A5 in appendix A.

4.6 Rubber Band System

The rubber band system works by using “rubber bands” around the outside of the payload ring to secure the payload during ascent. During separation, a motor is used to expand the rubber band to release the payload. Springs then push the payload away after separation of the rubber band has occurred. The advantage to this system is that the clamping during ascent does not require any input, once it is in place, it will require the motor to begin separation. The disadvantage to this system is that, much like the press band, it would be hard to ensure that the payload does not tip off during separation. See figure A6 in Appendix A.

4.7 J-Clamp System

The j-clamp design incorporated eight clamps mounted radially on the exterior of a ring that secures the individual clamps to the launch vehicle side of the mechanism as well as the linkage system that actuates all the clamps simultaneously to ensure separation of all clamps at the same time. Variable separation force is achieved through modulation of the motor driving the linkage plate. The advantage to this design is that it gives the user precise control over the rate at which the payload is pushed away from the launch vehicle, meaning that it is possible to impart low shock to the payload while still pushing it away with enough force to account for varying payload masses. The disadvantage to the j-clamp design at this stage of development is the complexity of the linkage system associated with the actuation of the individual clamps. The j-clamp system is one of the designs that made it through the decision-making process and is discussed in section 5. See figure A7 in Appendix A.

4.8 Polymagnet System

The Polymagnet system uses a new technology that prints the two poles of a magnet on one surface of rare Earth magnet. This allows the magnets to behave differently from normal magnets, most notably for this project the printed magnets can work as a latch, requiring only a small turn of the latch to separate the two halves of the magnets. This concept uses multiple magnets to secure the payload to the launch vehicle. A linkage system would turn the launch vehicle set of magnets causing the "latch" to disengage and begin separation of the system. The advantage to this system is that early, rough calculations pointed to the magnets being more than strong enough to secure the load during ascent. The disadvantage to this system is that the electromagnetic fields caused by the magnets could interfere with the sensitive electronics that may exist in the payload. This design is one of the designs that made it through the decision-making process and is discussed in section 5. See figure A8 in Appendix A.

4.9 Wedge System

The wedge design incorporates wedges placed around the outside of a ring attached to the launch vehicle side of the mechanism. The wedges would have corresponding wedges on another ring attached to the payload side of the mechanism. Locking would be achieved by jamming the two sets of wedges together to secure the launch vehicle ring to the payload ring. Upon separation, the upper ring would be rotated a slight amount, causing the wedges to unjam and separate. After wedge separation, springs mounted on pegs attached to the launch vehicle side of the mechanism would provide the force necessary to push the payload and the launch vehicle sides of the mechanism apart with the appropriate force required by the payload. The advantage to the wedge system is that the wedges can provide an ample amount of clamping force. The disadvantage to this system is that the wedges would require some sort of force to ensure that the sedges don't come apart during ascent. See figure A9 in Appendix A.

4.10 Bolt System

The bolt system uses a single rotating screw to secure the payload to the launch vehicle. This screw is almost the entire diameter of the launch vehicle and retracts into the launch vehicle side of the system when separation is complete. After separation of the screw and the payload is achieved, springs take over to provide the force necessary to push the payload away from the launch vehicle. The advantage to this system is that there are very few moving parts. The disadvantage to this system is that the friction in the screw may require too much energy to separate the system. This is the final design to make it through the decision-making process and is discussed in section 5. See figure A10 in Appendix A.

5 Selected Designs

In order to narrow down our designs, we first put every design into a PUGH chart (as seen in Appendix B1). In the PUGH chart, the three designs that are currently on the market already were entered for comparison. We selected the Planetary Systems Corporation system as our datum because it is what Orbital ATK currently uses for most of their payload launches.

5.1 Final Design Rationale

In the Pugh Chart, we compared each of our designs, the one Orbital ATK currently uses, and gave the design a (+) sign if we felt the design exceeded our datum, a (-) if we felt that the datum was better, or a (same) if we felt it was equal to the datum for each of the engineering requirements.

Based on our client's request, we eliminated the systems currently on the market based on weight, cost, or complexity. The designs that made it through our PUGH chart included the Polymagnets system, the Internal Locking Clamp System, the Bolts system, the Rubber Band Contracting System, and the J-Clamps system. We further evaluated these systems with a decision matrix.

From the Pugh chart, three designs ranked the highest: the bolt design, the J-Clamps design, and the Polymagnets design. In order to eliminate two of the designs, this team evaluated each system, the required energy outputs and the stresses. The Polymagnets system was based on the EMI's that the test system emitted. The Polymagnets system was based on the EMI's that the test system emitted. Based on these calculations, this team chose the Bolt design.

Table 4: Decision Matrix

Criteria	W.T.	Internal Locking Clamp		Bolt		Rubber Band System		J-Clamps		Press Band		Polymagnets	
		Score	W.S.	Score	W.S.	Score	W.S.	Score	W.S.	Score	W.S.	Score	W.S.
Material Homogeny	15	4	60	10	150	6	90	10	150	5	75	6	90
Material Cost	10	6	60	8	80	4	40	8	80	6	60	7	70
In-House Manufacturability	20	6	120	8	160	6	120	8	160	4	80	7	140
Potential Weight	15	3	45	5	75	2	30	6	90	3	45	10	150
System Complexity	20	5	100	9	180	5	100	4	80	6	120	4	80
Separation Force Modulation	20	3	60	5	100	3	60	10	200	2	40	5	100
Total	**100**		**445**		**745**		**40**		**760**		**420**		**630**
Orbital ATK Ranking				**1**				**3**				**2**	

5.2 Bolt Design

The Bolt design utilizes threads to separate the payload from the launch vehicle. This design consists of three main components. There are two internally threaded rings, one mounting to the payload, the other mounting to the launch vehicle. The only difference between the two is that the one mounted to the launch vehicle is two inches long while the one mounted to the payload is an inch long (the silver parts in figure 13). The third component is an externally threaded screw (red part in figure 15), that is screwed down into the bottom base one inch. The top payload side of the system is then torqued onto the screw until the faces of the two rings meet. To separate, a motor will rotate the screw counterclockwise completely down into the launch vehicle side of the system. Once the screw is in the launch vehicle portion, this will allow the springs to take control and push the payload away safely and uniformly.

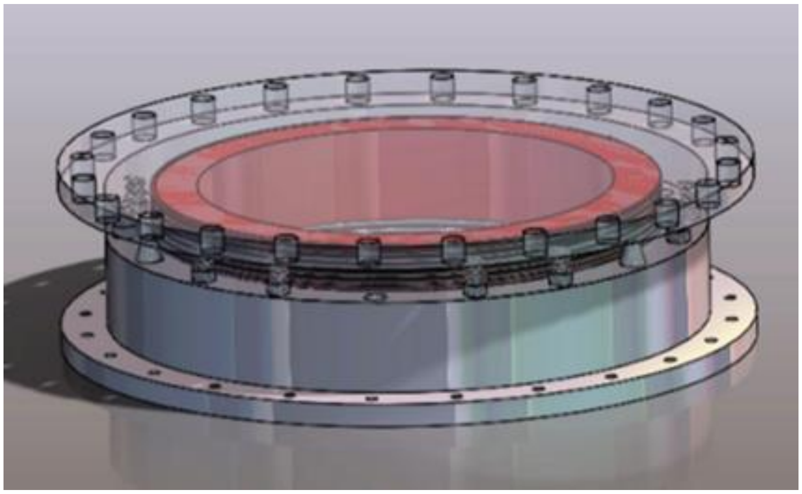


Figure 13: Bolt design model

This design ranked first by our client based on the simplicity of the design. The major advantage to this design that our client identified was it only has three components and one moving part. Less things moving means that there is less to go wrong. Our client identified three disadvantages: the threads potentially binding when a shear force from the launch is applied to the system, the potential of the payload rotating with the screw, and the payload having a high tipoff rate caused by the moment created when the last thread disengages. Moving forward, the focus will be to address these disadvantages. One way proposed to make the system stronger and prevent the threads from binding was by adding six small half inch cones along the ring of the internally threaded components. These cones are tapered by 15° for added strength. They also serve as a fastening tool to keep the payload from spinning when the screw rotates counterclockwise. To solve the large tipoff angle we will make the threaded component have four to six threaded sections to eliminate the moment caused by the disengagement of the final thread.

6 Proposed

This team presented this design to Orbital ATK for approval. During this presentation, the engineers expressed multiple concerns, including the center shaft buckling, the inability to handle the stresses, the ability to actuate the system, and the tip off angle during separation. In order to address these concerns, this capstone team deciding to go a different direction. By doing more in depth calculations, this team was able to adjust the design in order to address the concerns of the engineers. The completed iteration is shown in figure 14 below. The values for the in-depth calculations are listed in Appendix C.

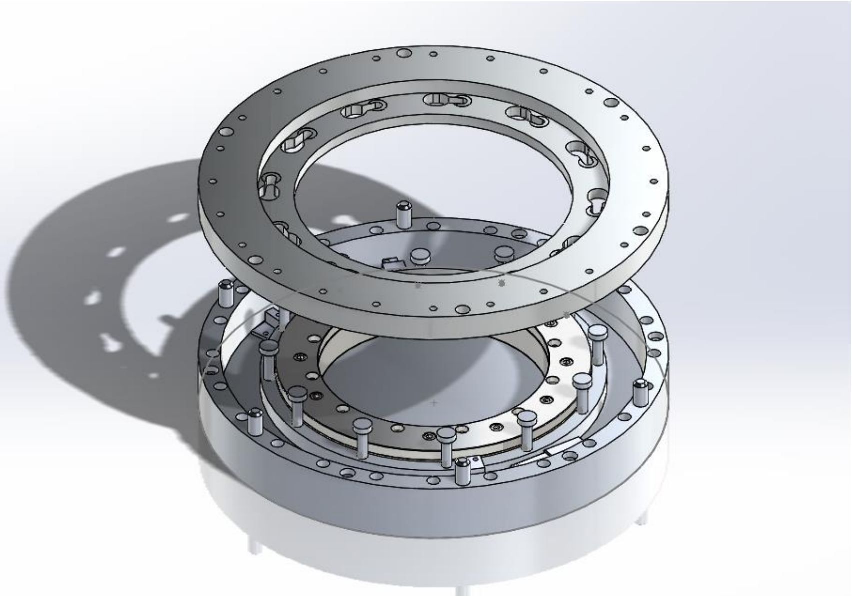


Figure 14: Completed iteration

The changes include removing the bolt and switching to CAM system. A CAM system is easier to actuate and requires less energy. There is less chance of buckling between the center shaft and the plates. By distributing the load over a larger surface with the CAM and t-hooks, the stresses in the system go down. This team also added alternating alignment pins between the top and bottom plates. These will eliminate any tip off angles as the system separates. These stresses along with their safety of factors are listed in table 5 below.

Table 5: Part stresses with factor of safety

Item	Stress (lbf/in^2)	Critical Stress (lbf/ in^2)	Factors of Safety
Ring (Axial + Bending) Buckling Stress	40000	5139620	128.49
Ring (Axial + Bending) Distributed over area	1057	40000	37.84295175
Ring (Axial + Bending) Coupled	2340	40000	17.09
T hooks (Flange)	2908	40000	13.76
T hooks (distance X= 5.6)	13990	40000	2.86
T hooks (distance X = 4.8)	5092	40000	7.86
T hooks (distance X = 2.8)	3492	40000	11.45
T hooks (Large Shaft)	7136	40000	5.61
T hooks (small Shaft)	13980	40000	2.86
T hook (head)	36	40000	1111.11
Alignment Pins	1038	40000	38.54

The key to actuation of this system is the custom slewing ring inside the design. The slewing ring takes no axial compressive force from the payload. This part of the systems rotates with power from a linear actuator and a 12-volt power supply; and the springs along the bottom plate lift the top plate away.

7 Implementation

The top and bottom plate, as well as the custom slewing were sent off to a machine shop to be manufactured. Table 6 outlines this team's implementation schedule as well as the dates each item was received or completed on.

Table 6: Implementation Chart

Implementation Tasks	Expected completion	Actual completion
Order parts & send work order to machine shop	22-Feb	22-Feb
T-hook tensile testing	2-Mar	2-Mar
Receive linear actuators, peripheral electronics and T-hook material	2-Mar	2-Mar
T-hook manufacturing	10-Mar	31-Mar
Send T-hooks off for anodizing	10-Mar	10-Mar
Receive Slewing ring	10-Mar	17-Mar
Receive manufactured parts and anodized T-hooks from machine shop	19-Mar	31-Mar
Test fit top and bottom plates with slewing ring and T-hooks	20-Mar	6-April
Develop linear actuator mounts	23-Mar	10-April
Test actuation and work unexpected complications	31-Mar	9-April

7.1 Design of Experiments (DOE)

The design of experiments the team conducted consisted of several tests changing design options for three components on the separation system. The components tested on the system were the T-hooks, top plate, and bottom plate. For each component, three characteristic features were chosen to evaluate using DOE. Performance figures were obtained through finite element simulation in SolidWorks.

7.1.1 T-Hooks

The three features tested on the T-hooks were the material, head thickness and main shaft diameter. Minimum factor of safety determined the performance of each DOE variant. Often the minimum factor of safety was found on the small shaft of the T-hooks where the threads met the larger diameter at a stress concentrator. The materials tested were Aluminum 6061-T6 and Steel 1020 cold rolled, the steel was chosen because it had a higher yield strength than the Aluminum. The head thickness was chosen as a characteristic feature because if it were too small, it would shear off during loading. Lower shaft diameter was identified as a possible point of failure and was chosen as the final feature to test using DOE. After testing the eight different combinations of the T-hooks, they were graded on the minimum factor of safety and weight. The final T-hook design as determined through DOE is shown in figure 15.

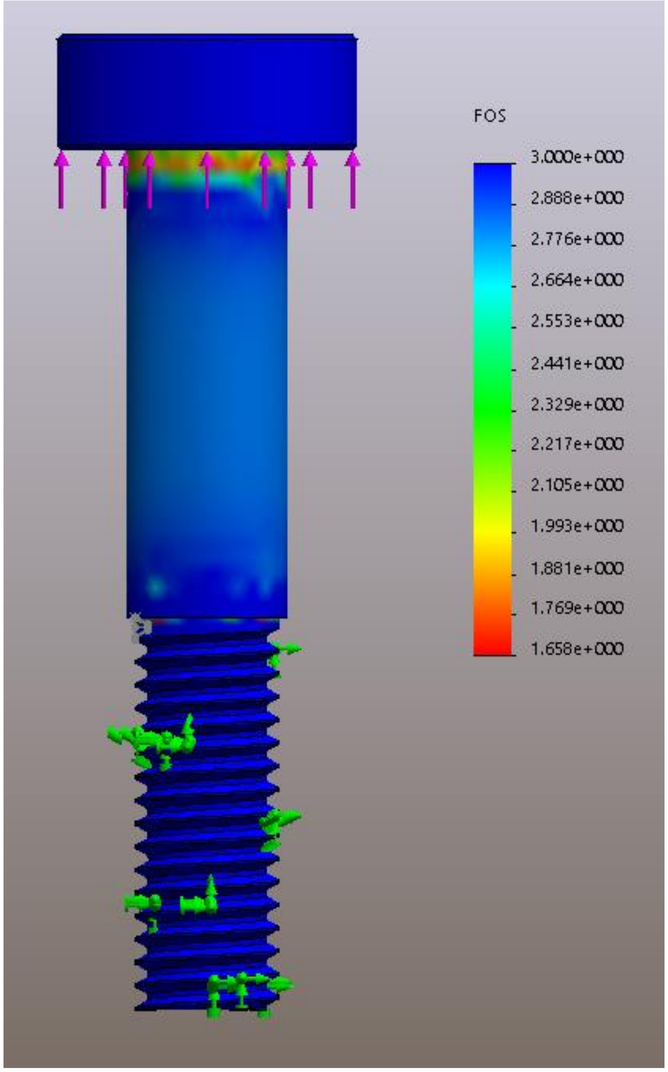


Figure 15 Final T-hook design determined through DOE Testing

The T-hook chosen for production has the thick head of 0.25 inches, the wide lower shaft diameter of 0.3125 inches and is made of Aluminum 6061-T6. The weight of the final design in 0.02 pounds. In-depth results of the T-hook DOE can be found in appendix D.

7.1.2 Top Plate

The three criteria chosen for DOE on the top plate were the material, lip thickness and lip width. The materials used for comparison were 6061-T6 Aluminum and 1020 cold rolled Steel. Steel was included in the DOE as a backup in case deflection with the Aluminum was too high. The dimensions concerning the lip were also chosen to see how they effected deflection. In the situation of the top plate, it was known that it would not yield, but deflection of the lip should be kept 0.01 inches (0.27mm). The top plate design chosen for manufacturing is shown in figure 16 below.

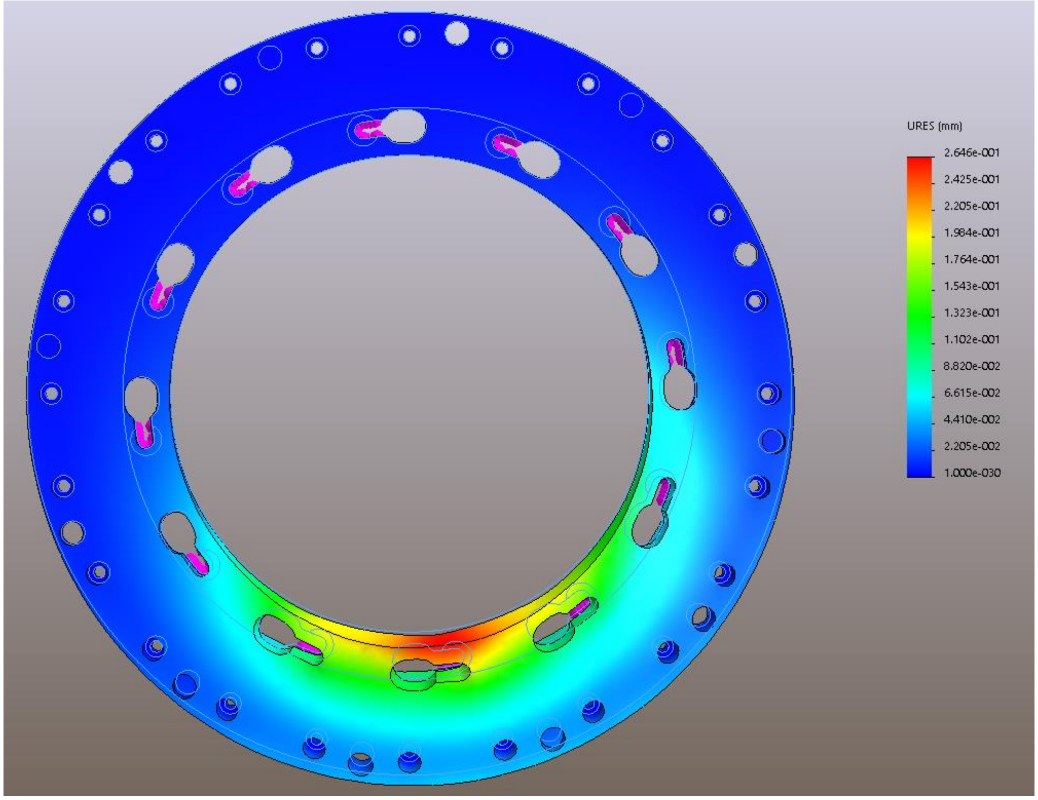


Figure 16 Final top design (as determined through DOE) FEA analysis

The final top plate design uses the thick lip thickness of 0.4 inches, the narrow lip width of 1 inch and is made from 6061-T6 Aluminum. Choosing Aluminum over Steel resulted in a significant weight reduction while keeping deflection below 0.01 inches. Appendix F contains in-depth DOE results for the Top plate.

7.1.3 Bottom Plate

For the bottom plate, the three features tested using DOE were the material, the base plate thickness and the width of the outer wall. The materials used for comparison were 6061-T6 Aluminum and 1020 cold rolled Steel. Steel, again, was used as a backup material in the event that deflections of the aluminum exceeded 0.01 inches (.27mm). Base thickness is the feature that was identified to have the strongest correlation to the deflection of the base, so it was included in the DOE. Finally, the width of the wall was included because it was not known whether it would have an effect or not. Deflection was used as the value to measure performance of each design. Figure 17 shows the FEA simulation of the production design

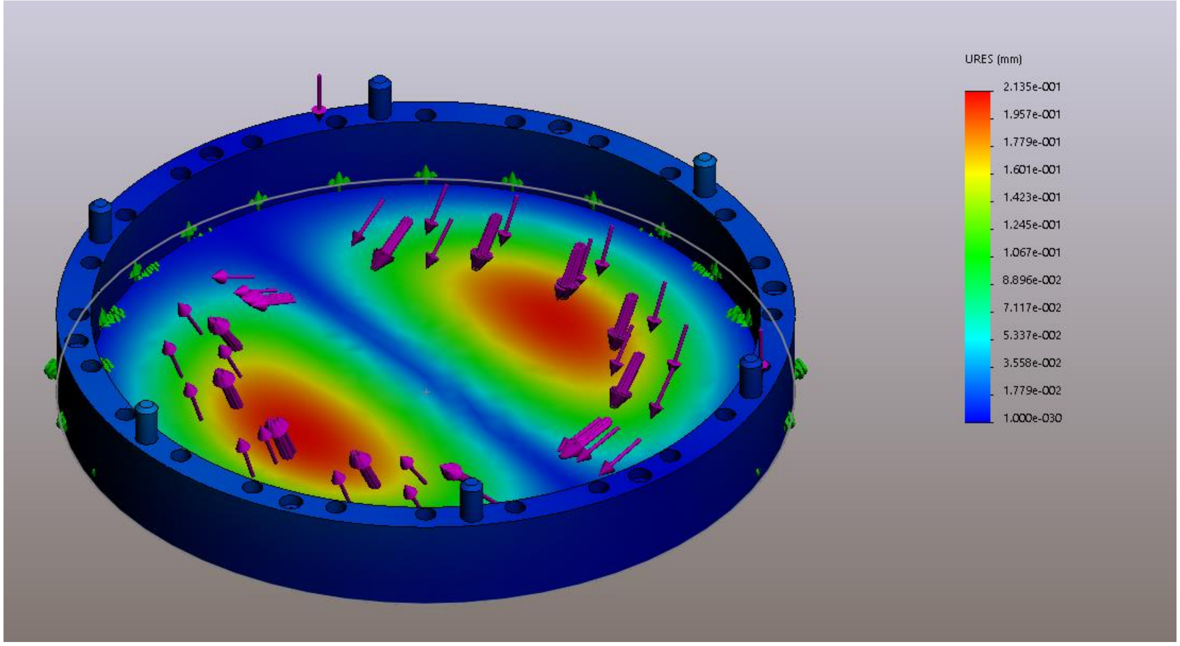


Figure 17 FEA simulation of the bottom plate showing maximum deflection

The final design has a base plate thickness of 0.4 inches, a wall thickness of 0.75 inches and is made of Aluminum. Using aluminum resulted in deflections of less than 0.01 inches so Steel was not needed in this case. Appendix G contains in-depth.

7.1.4 T-Hook Instron Test

After doing hand calculations and a finite element analysis (FEA), the client suggested then requested for a tensile test to be done on the T-hooks to confirm all the results of both the hand calculations and the FEA. The team built a set of three T-hooks to perform a tensile test until failure on two of the three with one being subjected to a deflection test to see the maximum needed to permanently deform the T-hook. The team is presently reaching into methods to perform the deflection test; however, the tensile test was done and provided enlightening results.

Once the team made the two T-hook samples, the team approached Dr. Cornel Ciocanel, a mechanical engineering instructor and researcher, for his assistance in performing this test. Prior to doing the test and mount construction, the team and Dr. Ciocanel analyzed the design and identified three possible failure points which were; the T-hook head shear off, the threading shear away, and final the small thread shaft entirely breaking snapping. After receiving instruction to build mounting pieces for the instron to hold onto that will test both the shearing of the T-hook's head and shearing of the threads at the same time, the testing of the hooks could be conducted.

On March 2, 2017, the team's appointment with Dr. Ciocanel for the instron test came. After the team, were briefed on the processes Dr. Ciocanel was doing with instron to ensure accurate result and safety-ware was acquired the testing began. Both T-hook samples were subjected to same tensile test and passed the expected load they will be seeing which was 1,339-lbf (5969-N); however, the sample immediately began yielding after that. Below are both samples tensile test graphs.

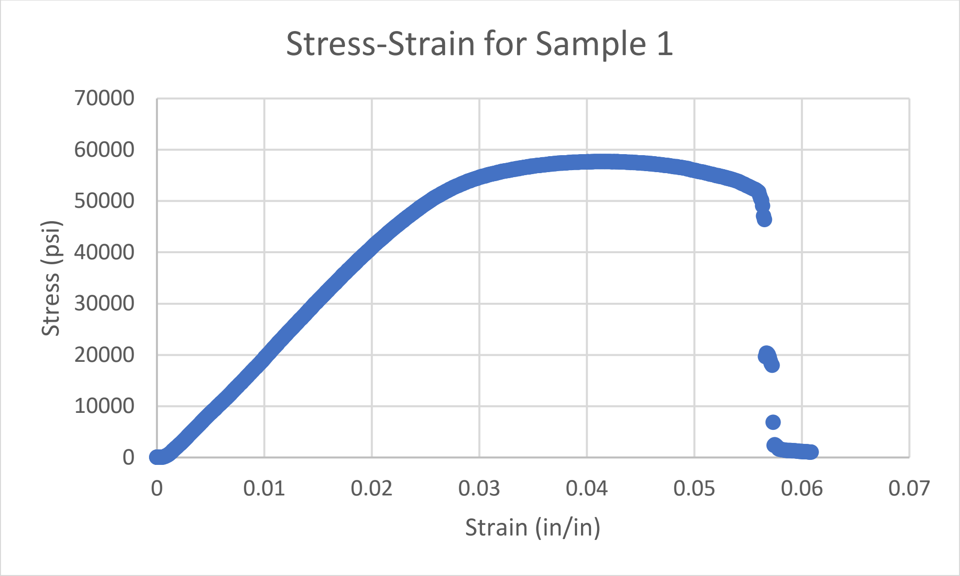


Figure 18: Sample 1 Instron Test

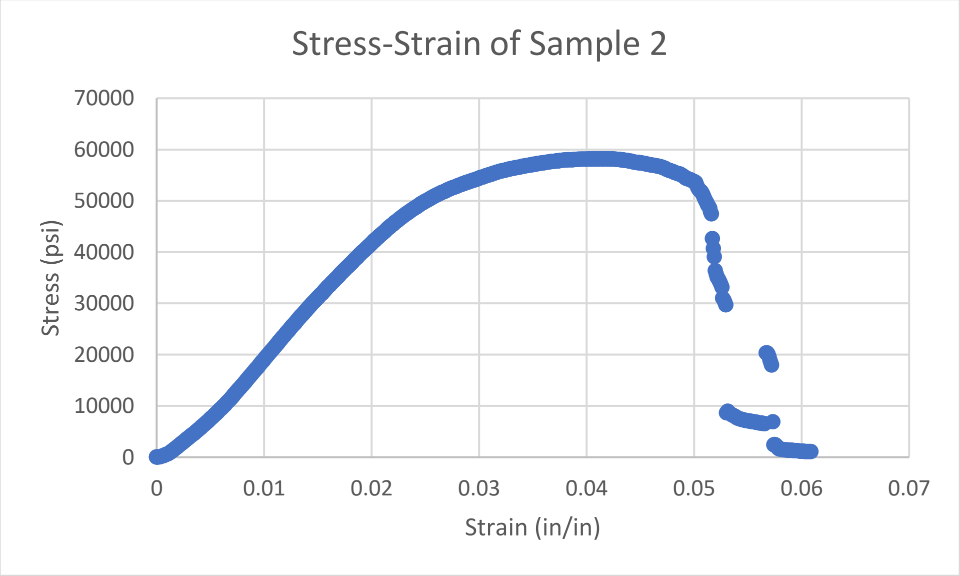


Figure 19: Sample 2 Instron Test

After completing the instron test, the team analyzed the data and calculated the T-hook’s manufactured factor of safety. For both samples, their factor of safety was 1.0, meaning that the 1.25 factor of safety was not met for those sample. The reason for the failure was because the ¼”-20 threads minor diameter was smaller than 0.25-inches resulting in a smaller area holding the loads. Below are pictures of the two specimens after the instron tests.

Figure 20: Sample 1 After Instron Test

Figure 21: Sample 2 After Instron Test

Even though sample 1's (figure 20) fracture points is difficult to see, both samples 1 & 2 fractured in the same location. The fracture occurred along the minor diameter of the thread. After the test results and calculating a factor of safety of 1.0, this prompted the team to begin an iterative process to find a thread size that will not fail below the required factor of safety of 1.25.

After realizing this, the team begin iterating the thread design. The team seeking a thread that would not only just hold the required load but also that would fit the team's factor of safety of 1.5. After intensive research and calculations, the team settled on a 5/16"-18 thread. The minor diameter for this thread was a ¼" fitting the original expected diameter. Once the team made the new T-hooks with the 5/16"-18 thread, the team approached Dr. Ciocanel with his assistance in another instron test. Figures 22 is the stress-strain curve of the new design.

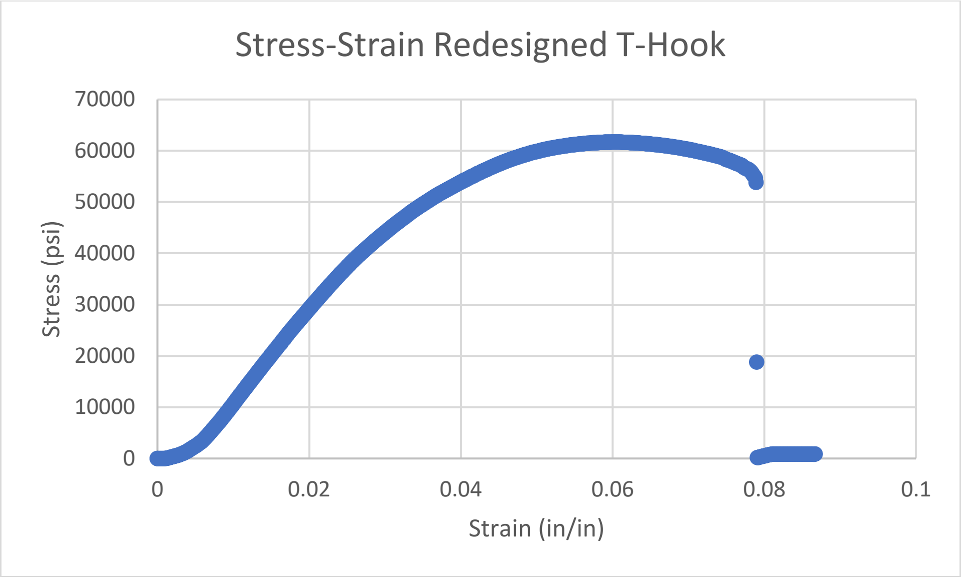


Figure 22: Redesigned T-Hook Instron Test

After doing the instron test, the team regrouped and began calculating for the yielding load. After analyzing the data, the team was excited to see that the redesign held up to the expected load of 2,019-lbf which was with the team's factor of safety of 1.5. The load at which the 5/16"-18 threaded T-hook began yielding at 2,023-lbf. With these results, the team was confident that the T-hooks would be able withstand the strength testing.

7.2 Manufacturing

Once the team received approval from their client, manufacturing and purchasing began to bring the design to reality. The top and bottom plates along with custom slewing ring were dispatched to Tahl Inc. for manufacturing. Originally, the team was planning to dispatch the T-hook to Tahl Inc; however, after producing three T-hooks for a tensile test, per the client's request, the team was convinced that the T-hooks could be manufactured in Northern Arizona University's fabrication shop. With only those four components being manufactured everything else was purchased to ensure the designs functionality. A bill of materials is provided in Table 7 below including everything that is needed to bring this first iteration of the design to life.

Table 7: Bill of Materials

Bill of Materials				
Quantity	**Part Description**	**Model or Part Number**	**Manufacture**	**Individual Price**
1	Bottom Plate	---	Tahl Inc	$1,120.92
1	Top Plate	---	Tahl Inc	$1,710.92
1	12 Hole Custom Slewing Ring	---	Tahl Inc	$378.90
1	Slewing Ring	PRT-01-200	IGUS	$535.00
12	T-Hooks	---	Capstone Team	
2	L-16 Actuonix Linear Actuators	L-16-30-150-12-S	Actuonix	$70.00
2	Linear Actuator Mounting Brackets	---	Capstone Team & NAU Shop Managers	---
6	Springs	9657K352	McMaster-Carr	$8.84 per pack of 6
1	Timing Relay	TIMER_RELAY	Actuonix	$90.00
48	¼”-20 X 2” Socket Head Bolts	---	---	---
12	¼”-20 X 1” Socket Head Bolts	---	---	---
6	¼”-20 X 0.5” Socket Head Bolts	---	---	---
12	6mm X 1" Socket Head Bolts	---	---	---
8	8-32 Socket Head Bolts	---	---	---
48	¼”-20 Hex Nuts	---	---	---
6	¼” Lock Washers	---	---	---
10	8-32 Hex Nuts	---	---	---
1	Bottle of LocTite	---	LocTite	On-Loan
1	GW Instek GPS-4303 Power Supply	---	Instek	On-Loan
1	DPDT Switch Kit	SWITCH KIT	Actuonix	$6.00

8.0 Testing

For the testing aspect of the design, our client provided the team with a list of tests he would like to see the design pass in order to consider the system a success. Unfortunately, due to Orbital ATK’s testing facilities being booked for company projects, our client revised the list of required tests that were needed for the design. Along with required tests, our client suggested additional tests that he would like done if time permitted. In table 8 below is the list of tests that were required and suggested for the design.

Table 8: List of Tests for the design

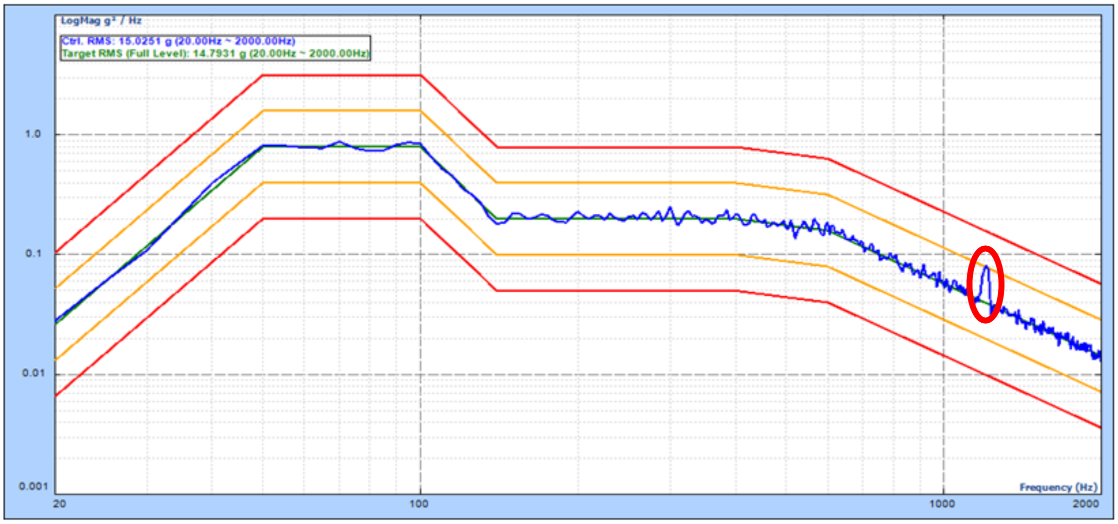
Test		Hierarchy
Strength	Axial	Required
	Shear	Required
	Bending	Required
Performance	Tip-Off	Required
	Actuation	Required
	Vibration	Suggested
	Variable Separation Force	Suggested
Environmental	Temperature Survivability	Suggested

8.0.1 Vibration and Shock

One of the tests the team performed was a vibration test. Figure 23 shows the setup of the test done at Embry-Riddle Aeronautical University. A random vibration test ranging from [redacted] was performed.

Figure 23: Vibration Testing at Embry-Riddle

The mounting hardware provided to this team for this test failed before the test could be completed. The designed system did withstand the conditions up to 14.79g for a period of 1 minutes and 32 seconds. Figure 24 shows the vibration results. The red circle shows the peak where the wood testing mount failed and tripped the vibration table on a thermal overload. Shock was not able to be tested because the levels needed were too high for the vibration table.



Level: 100.00 %
Velocity Pk: 0.602 m/s
Remaining: 00:02:07
Block size/Lines: 1024/400
Delta frequency: 5.000000 Hz

Drive Pk: 10.0V
Control RMS: 15.03 g
Total elapsed: 00:01:32
Frame time: 0.2 s

Est. disp. (PkPk): 0.004 m
Target RMS: 14.79 g
Full level elapsed: 00:00:53
DOF: 64

Figure 24: Vibration Test Results

8.0.2 Bending Loads

A large moment load of [redacted] lbf-in was given to us that the system had to withstand. Since the team did not have access to a testing facility for this, a complex testing procedure was performed using a hydraulic piston. This setup can be seen in Figure 25. Since the hydraulic piston gauge was in psi, more calculations had to be done to apply an equivalent moment load of [redacted] psi to the system. The design successfully passed this test.

Figure 25: Bending Load Test

8.0.3 Shear Loads

For the shear testing, the team designed their own method of testing using a hydraulic piston and a separate hydraulic piston base. This test also had a complex testing procedure and mounts. The system needed to withstand a shear force of [redacted] lbf. Using a hydraulic piston, [redacted] psi was calculated and applied in a shearing direction. The setup is shown below in Figure 26. The design successfully passed this test as well.

Figure 26: Shear Load Testing

8.0.4 Axial Loads

To test the axial loads, a compression test was performed. This was performed using an Instron machine. The system needed to withstand [redacted] pounds of compression. The Instron took the system to [redacted] N. The system passed the test successfully. Figure 27 is a picture of the instron machine.

Figure 27: Instron Compression Testing

8.0.5 Tip-Off Angle and Separation Force

In order to test the system’s tip off angle, a testing apparatus was built. This apparatus was approximately five feet tall and three feet wide. Figure 28 shows the testing mount. By placing a checkerboard background of inch large squares behind the system and using a camera with 960 frames per second, the team could record the system actuating in slow motion. By counting the frames over the distance and measuring the angle when the system was in line with the camera with a protractor, the team could measure the tip-off angle. For the design to pass, the tip off could not exceed more than 1 degree per second. The initial angle was approximately 1.23 degrees per second. This was caused by the T-Hooks' middle shaft being different lengths and the testing fixture not being level. By readjusting the T-Hooks' heads to the same distance away from the slewing ring, the team was able to bring the tip-off angle down to approximately 0.4 degrees per second. Therefore, since the angle is less than 1 degree per second, the system passed the test. Separation force was not completed due to time constraints. The team had planned on measuring each spring using a force gauge to ensure all springs characteristics were similar.

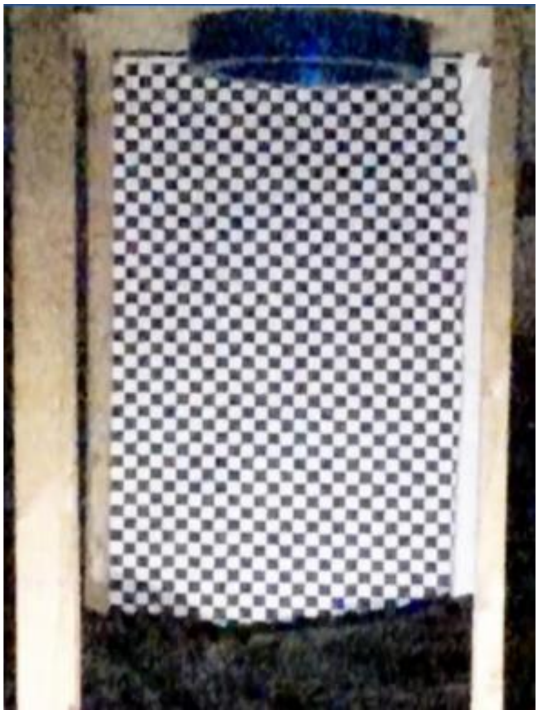


Figure 28: Tip-Off Angle Testing

9 Conclusions

From the team charter drawn up in fall 2016:

> *Our main team goal is to successfully design a Low Shock Payload Separation System in the allotted time. We plan to learn about the systems that entail this device and work great together as a team. We want to take full advantage to learn all we can about Orbital ATK and what it has to offer. Our members are willing to commit to the highest level to successfully complete our project. We are aiming to get an A in this course and accomplish the goals set by our client.*

The team feels that they have successfully met the goals that the team set for themselves and met all the engineering and client requirements with the system they designed. Although our initial point of contact could not make our presentation during UGRADS, a liaison came in his place and was impressed by our system.

From this team's charter drafted in fall 2016:

[1] The team will meet every Wednesday at 5:30pm and Monday at 3:00pm in the Internet Cafe or Capstone Room to discuss our progress, upcoming reports, and the meeting to follow with Mr. Hengl.
[2] The meeting with Orbital ATK will occur every Thursday at 4:00pm in the engineering conference room on the third floor.
[3] Every meeting is mandatory and every member must come prepared to the meeting.
[4] We expect the top level of effort and commitment from every member of the team.

[5] Each meeting will have an outline of what we are going to cover. This will eliminate all the side talk, getting off the main subject at hand, and make meetings more efficient.

[6] Following all the outlined topics, members will be allowed to bring up other small topics they wish to discuss.

[7] Duties for who will do each section of each assignment will be negotiated and determined by all members of the group. This allows everyone's voice to be heard and acknowledged.

[8] If disagreements arise the model rocket discussed below in section 6 will be implemented to allow everyone's side to be heard and clear up confusion. This will most likely settle most arguments but if it comes to where there is an ongoing argument that no side is agreeing to the "Robert's Rules of Order" will be put into effect. A move to take a vote will occur and a vote to move on and decide will happen.

Overall, the ground rules were followed. There were a few exceptions like meetings, that did not happen because other circumstances. Since this group encountered many issues with communication and dedication, a few members took it upon themselves to complete most tasks.

The specific technical lessons that this team learned was the process of taking a design from calculations, to manufacturing, and then to testing. The calculations proved to be difficult because there were many more factors effecting the system then we had initially thought. Although some of them were calculations that we had seen before, there were a few that we had not. With manufacturing, we learned how companies deal with contracts that are not upheld. Although we were not able to utilize the knowledge for our design, it is something that we can take with us in the future. We learned how to come up with our own experiments to test certain conditions when the resources are not available to you (for example, our shear and bending tests).

The main thing this capstone has taught this team is learning how to learn. We were not given all the equations and just expected to plug in the values. We were given a complex real world problem and expected to design a system to meet all the criteria given.

9.1 Contributions to Project Success

Looking back at the year, two main factors contributed to the project success. Individual dedication and resolve contributed were major factors in the success of the project. When the project hit a low point, most of the team banded together and pressed forward. After the team presented their final design for the first semester to the panel of engineers at Orbital ATK, the maturity of the design was put into question. Instead accepting defeat and giving up, the team rallied and took their winter break to design a completely new design. It was motivation and individual dedication that allowed the project to be a success.

Along with motivation and dedication, the team's resolve proved to be pivotal as well. In order for the team's system to be a success in our client's eyes, it needed to pass a set of required tests. After learning that the team would be unable to use Orbital ATK's testing facilities to test the design, the team began devising a plan to test our system on campus. The team designed and built the testing fixtures for which the design would be tested. With this resolve, the design was a success and received the approval from our client during the undergraduate symposium.

9.2 Opportunities for Improvement

Overall, the team performed well; however, there was two aspects that were weak. Communication and overall team dedication are critical in team-based projects. Most aspects of the project were done by a few members on the team, not by all members. Also, the communication when something is being done was spoken to one or two people which left a major gap in knowledge of what is happening with the design to the rest of the group. In the end, the team did pull together and succeed with a functional separation system for Orbital ATK.

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Appendix A: Design Sketches

The legs of riffle
beetles hold onto
underwater Substrates
in fast currents
using large, strong
terminal claws.

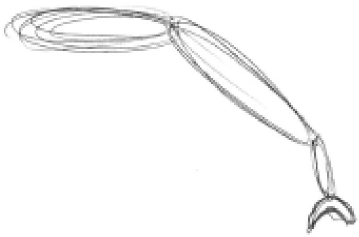


Figure A1: Bio-inspired-riffle beetle legs

Cucumber plant
tendrils twist due
to an asymmetric
contraction of an
internal fiber of
Specialized Cells

Figure A2: Bio-inspired-plant tendrils

Suction.

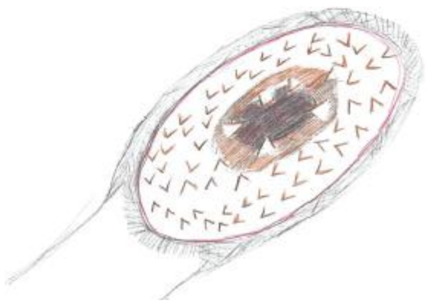


Figure A3: Bio-inspired-jawless mouth of lamprey

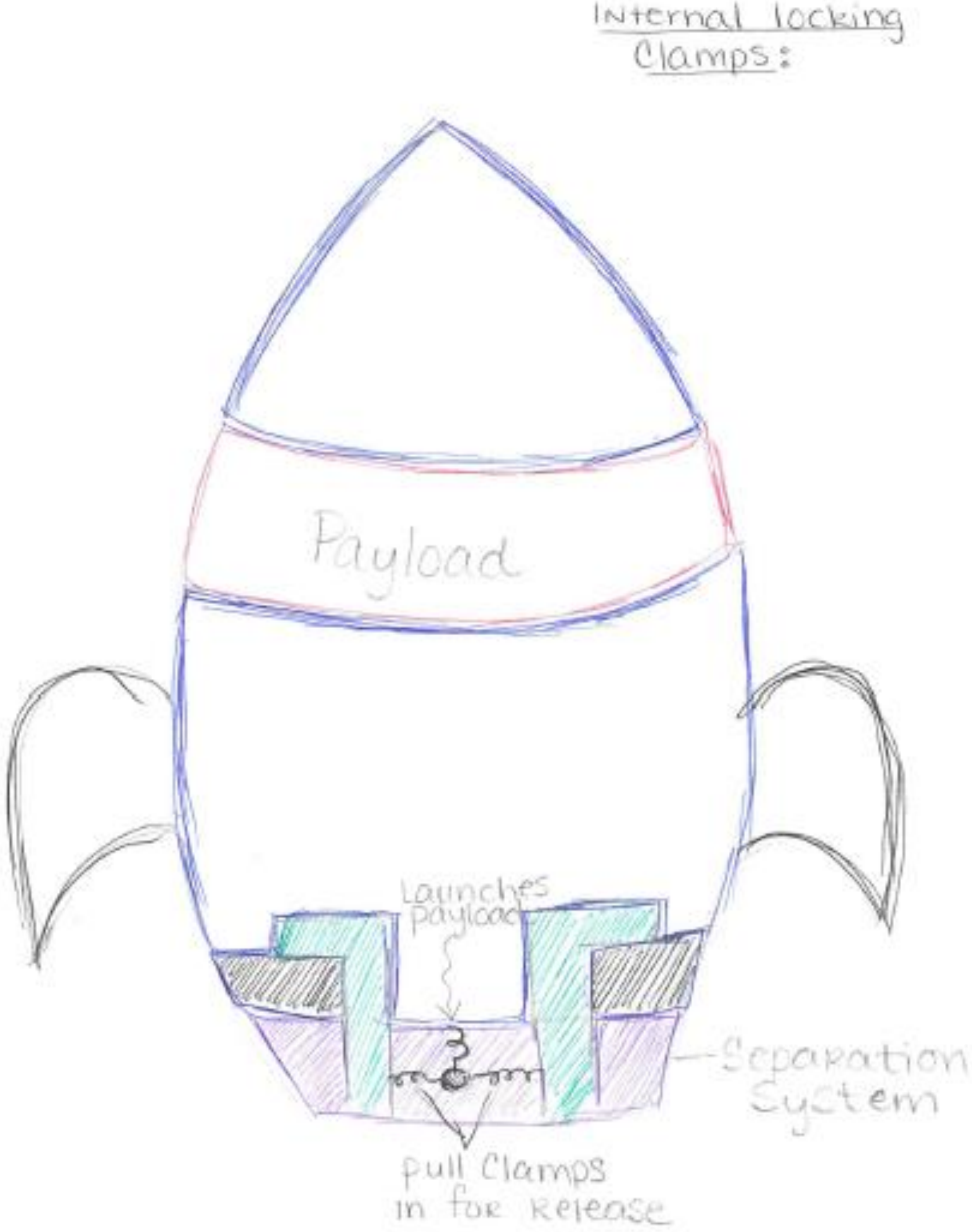
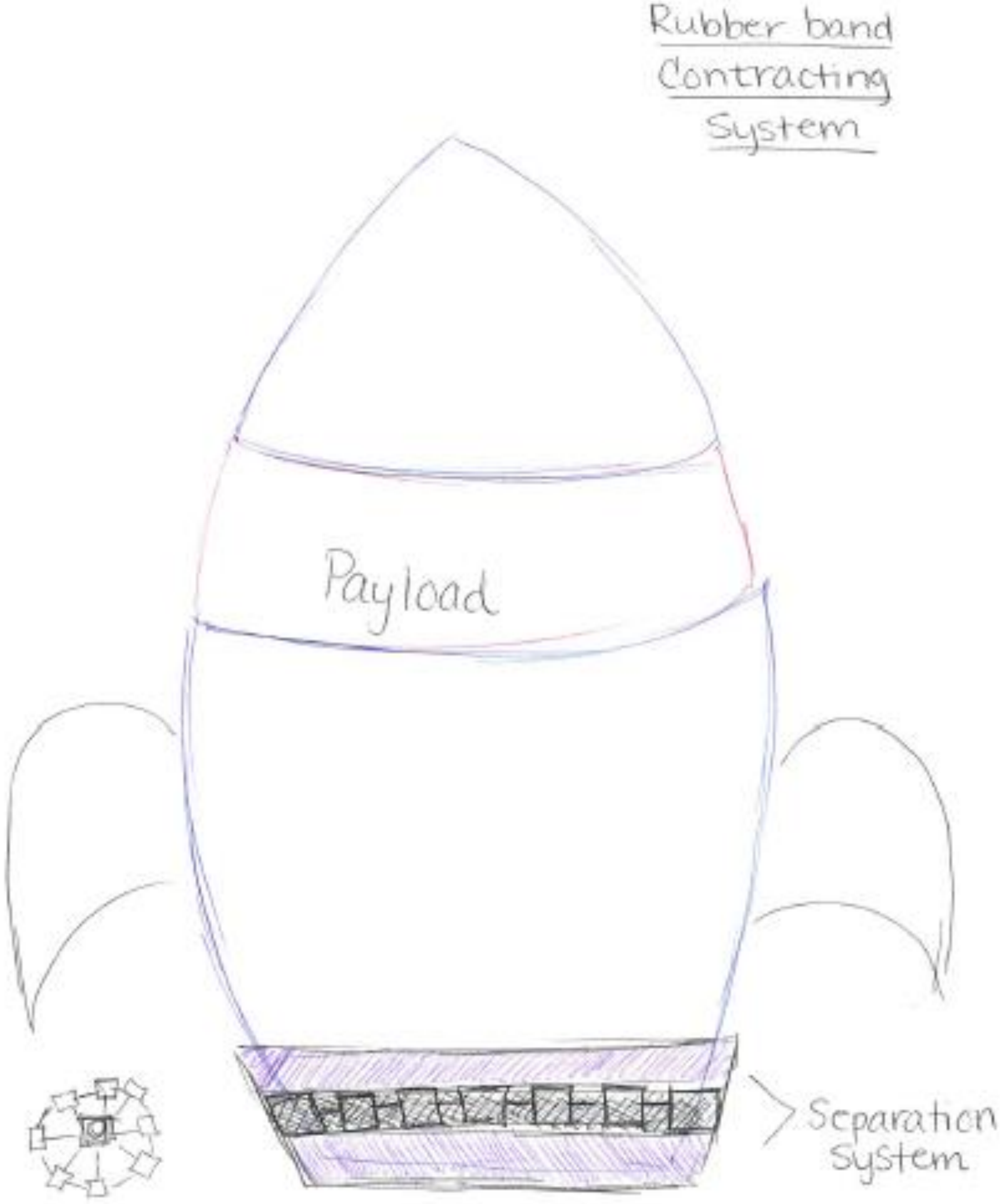


Figure A4: Internal locking clamps system

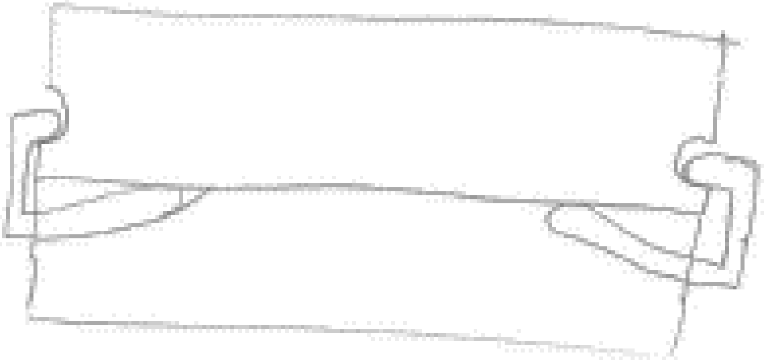
Figure A5: Clamp band system

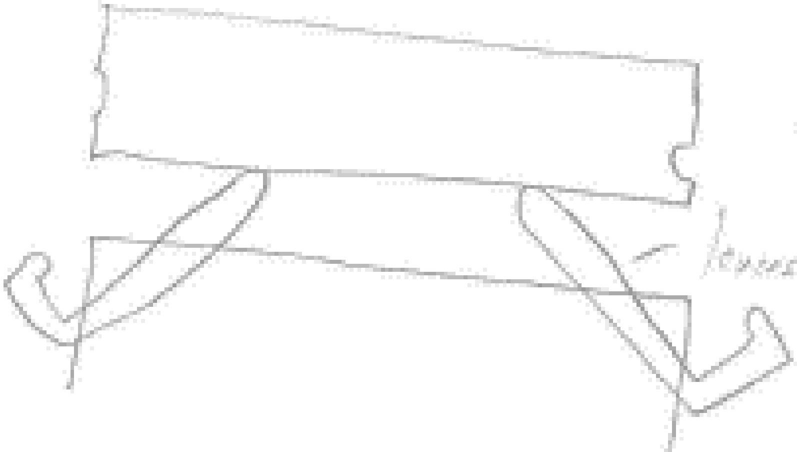


When System releases, Separation System expands to release. A spring pushes the payload up.

Figure A6: Rubber band contracting system

The J-Clamp Design

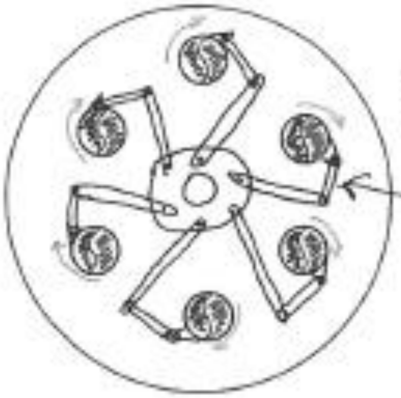




levers push payload away, eliminating need for springs

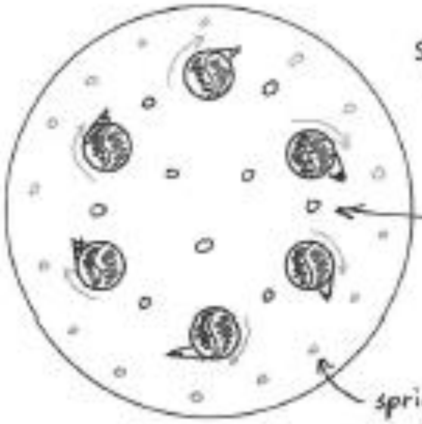
Figure A7: The J-clamp system

Polymagnets



Shuttle ring
under side

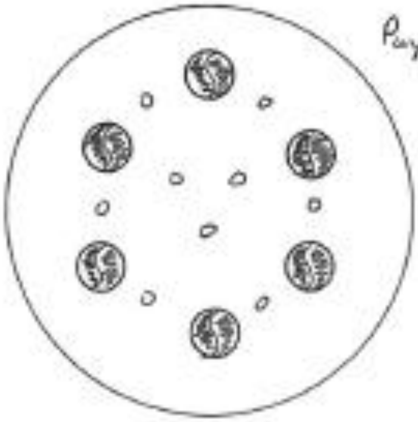
A single motor will rotate the polymagnets to release the rings



Shuttle ring
Top side

raised male pegs to assist in shear load support

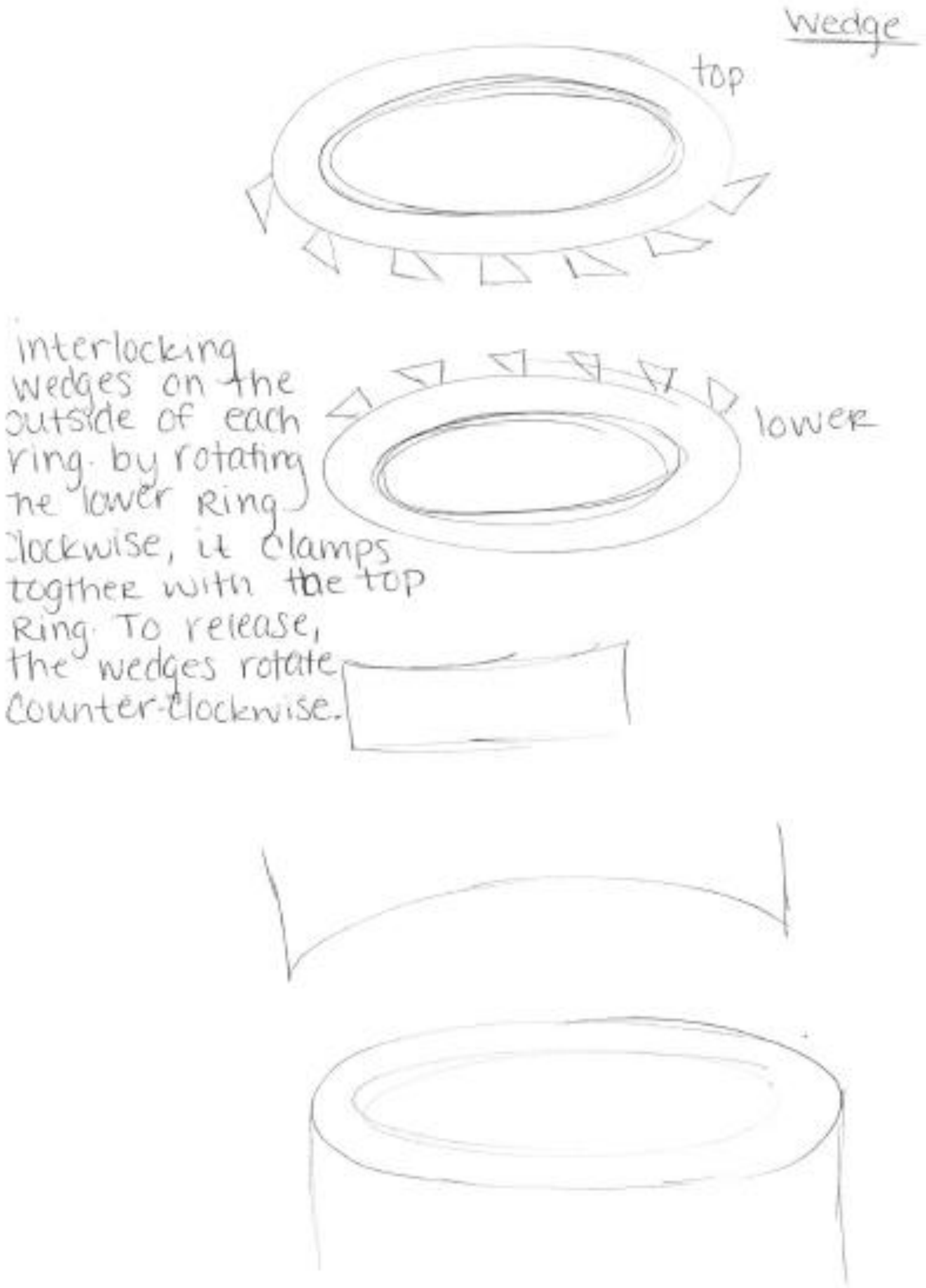
springs to push the payload away from the shuttle



Payload ring

The magnets on the payload ring are fixed and the female peg spots for the male peg to sit in them and aid in the shear load resistances.

Figure A8: Polymagnets system



interlocking wedges on the outside of each ring. by rotating the lower Ring clockwise, it clamps togther with the top Ring. To release, the wedges rotate Counter-clockwise.

Figure A9: The wedge system

:ws

(2) half threaded in (1) & (3) for launch. When payload launches, (2) mechanically threads down into (3) releasing from (1). Springs push payload away from Separation System. (May need to make threaded Components larger)

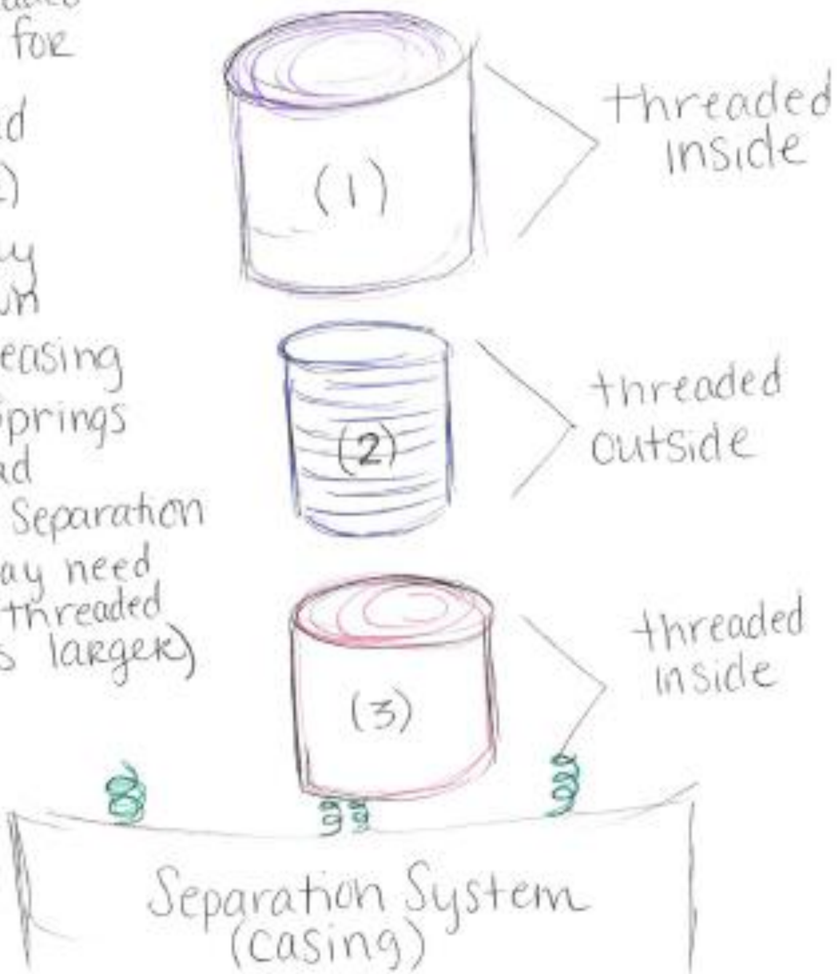
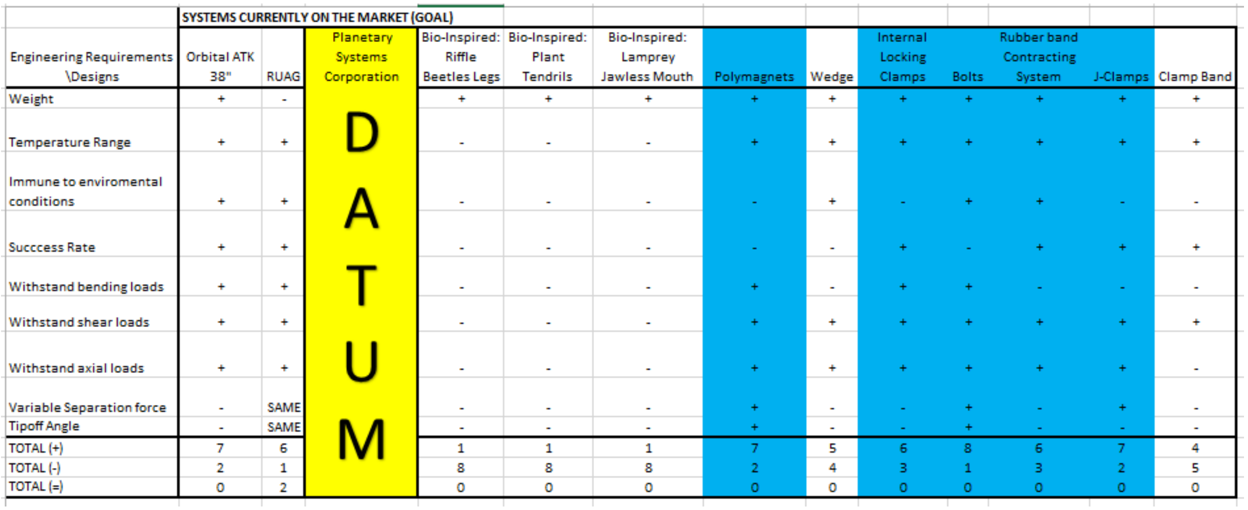


Figure A10: The bolt system

Appendix B: Pugh Chart

Table B1: PUGH Chart



	SYSTEMS CURRENTLY ON THE MARKET (GOAL)													
Engineering Requirements \Designs	Orbital ATK 38"	RUAG	Planetary Systems Corporation	Bio-Inspired: Riffle Beetles Legs	Bio-Inspired: Plant Tendrils	Bio-Inspired: Lamprey Jawless Mouth	Polymagnets	Wedge	Internal Locking Clamps	Bolts	Rubber band Contracting System	J-Clamps	Clamp Band
Weight	+	-	DATUM	+	+	+	+	+	+	+	+	+	+
Temperature Range	+	+		-	-	-	+	+	+	+	+	+	+
Immune to enviromental conditions	+	+		-	-	-	-	+	-	+	+	-	-
Succcess Rate	+	+		-	-	-	-	-	+	-	+	+	+
Withstand bending loads	+	+		-	-	-	+	-	+	+	-	-	-
Withstand shear loads	+	+		-	-	-	+	+	+	+	+	+	+
Withstand axial loads	+	+		-	-	-	+	+	+	+	+	+	-
Variable Separation force	-	SAME		-	-	-	+	-	-	+	-	+	-
Tipoff Angle	-	SAME		-	-	-	+	-	-	+	-	-	-
TOTAL (+)	7	6		1	1	1	7	5	6	8	6	7	4
TOTAL (-)	2	1		8	8	8	2	4	3	1	3	2	5
TOTAL (=)	0	2		0	0	0	0	0	0	0	0	0	0

Appendix C: Calculations

Table C1: Calculation Values

Component	Calculations	Equation	Symbol	Value
Ring	Axial & Bending Compression Force		A	0.75 in^2
			I	0.9765 in^4
			r	1.141
			K_cantilever	2
			K_fixed-pinned	0.7
			σ_cr2	5,139,620 psi
			σ_cr0.7 (psi)	41,956,083
			σ_al6061T6 (psi)	40,000
Ring	Axial & Bending Compression Force		S	32.40 in^2
			F_max	1,296,000 lbf
			F_SA	202 lbf/in^2
			M	110 lbf/in
			F_SB	798 lbf
			σ_M	798 lbf/in^2
			σ_actual	1,000 lbf/in^2
Ring	Bending Compression Force		2*F_SB*R	28,000 lbf-in
			F_SB	1,931 lbf
			σ_actual	1,931 psi
T-Hooks	Moment		M	239 lbf/in
			F_5.6	1,339 lbf
			F_4.8	574 lbf
			F_2.8	335 lbf
T-Hooks	Spring Force and Moment		F_st	120 lbf
			A_Flange	0.2356 in^2
			A_LSC	0.096 in^2
			A_SSC	0.031 in^2
			I_Flange	7.388 in^4
			I_LSC	3.011 in^4

			I_SSC	0.985 in^4
T-Hooks	Spring Force and Moment		σ_Flange	9,079 psi
			σ_LSC	13,980 psi
			σ_SSC	22,278 psi
			σ_SAE6061ys	40,000 psi
T-Hooks	Shear Force		F_ST	120 lbf
			A_HS	0.27488 in^2
			σ_HS	437 psi
Alignment Pins	Shear Force		F_SS	2,445 lbf
			σ_S	49,809 psi
			σ_SP	6,226 psi
Slewing Ring	Energy Required		F_ST	120 lbf
			f_al6061S	0.42
			f_al6061D	0.38
			F_SST	50.4 lbf
			τ_R	282.74 in-lbf
			H.P.	0.054 hp
			W_T	40.14 W
			W_P	40.14 W

Appendix D: T-hook DOE

Table D1 T-hook DOE Results

	Variable Actual values					
		low (-1)	high (+1)	units		
	Material	40	72.8	Kpsi		
	Hook Thickness	0.125	0.25	in		
	Shaft Diameter	0.25	0.35	in		

			Material	Hook Thickness	Small Shaft Diameter	
		I	x3	x2	x1	FOS
1	Al, thin, narrow	1	-1	-1	-1	1.23
2	Al, thin, wide	1	-1	-1	1	1.194
3	Al, thick, narrow	1	-1	1	-1	1.358
4	Al, thick, wide	1	-1	1	1	1.658
5	St, thin, narrow	1	1	-1	-1	1.539
6	St, thin, wide	1	1	-1	1	1.485
7	St, thick, narrow	1	1	1	-1	1.665
8	St, thick, wide	1	1	1	1	2.038
	Resultant ß's	1.520875	0.160875	0.158875	0.072875	

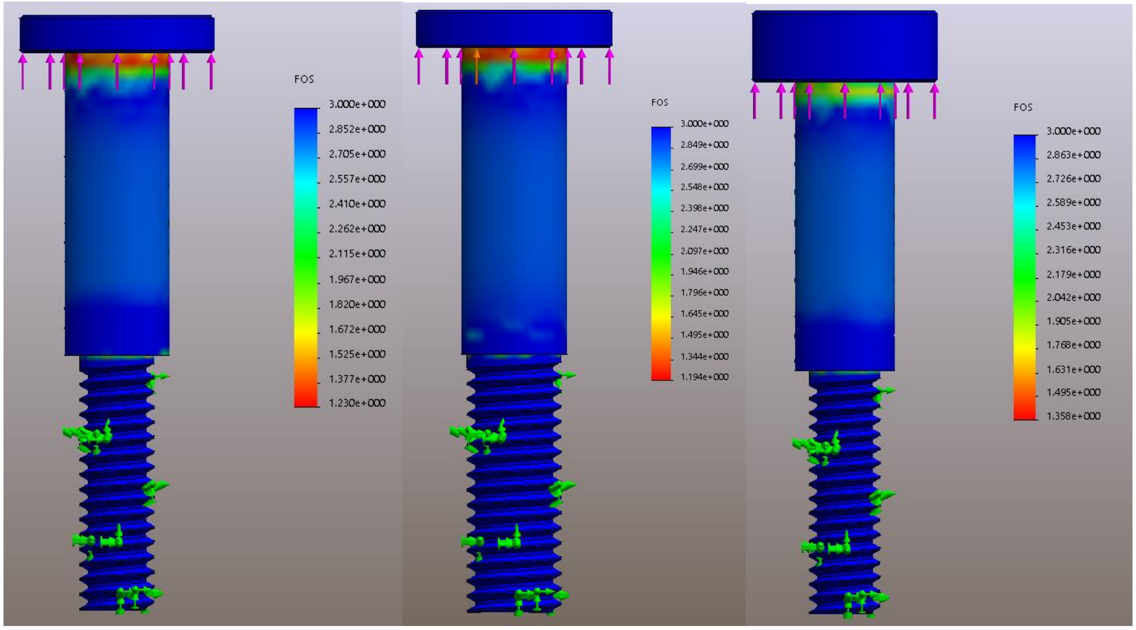


Figure D1 Variants 1,2 and 3 respectively

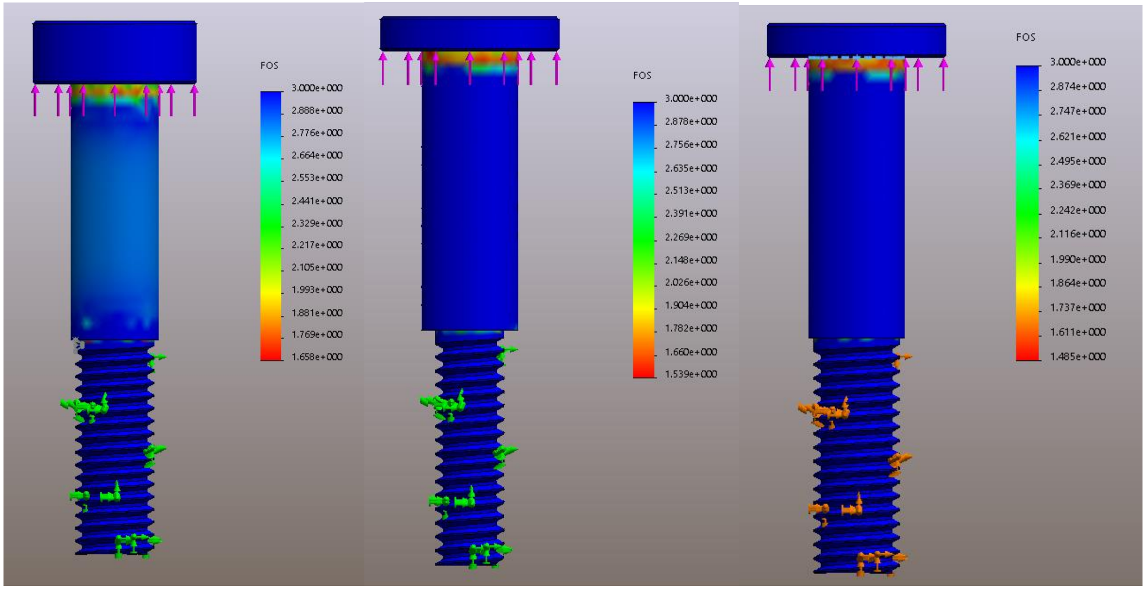


Figure D2 Variants 4,5 and 6 respectively

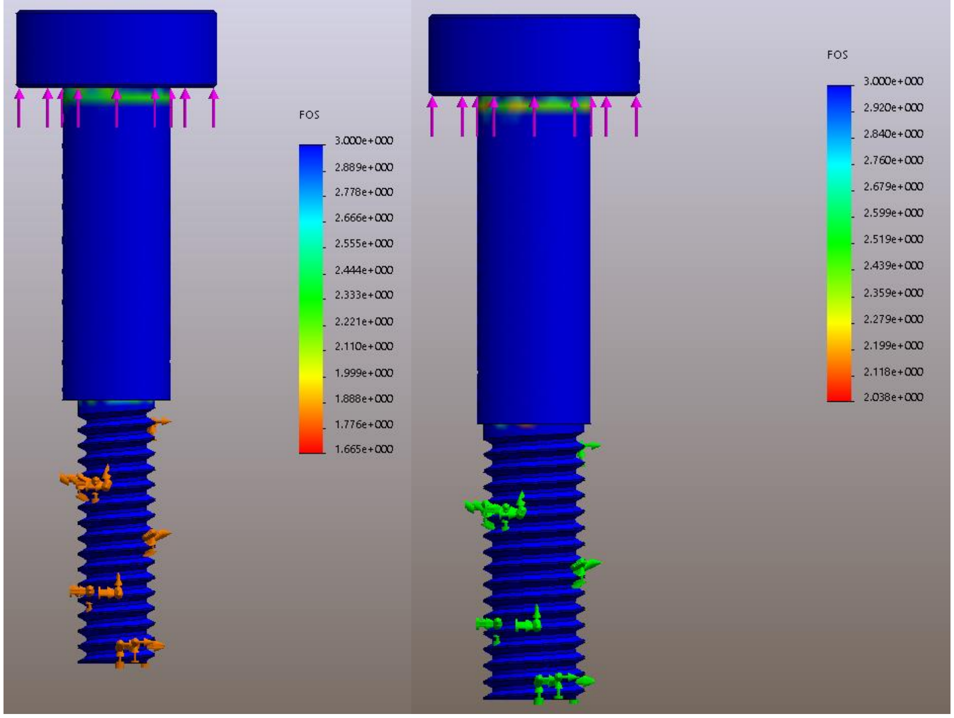


Figure D3 Variands 7 and 8 Respectively

Appendix E: Top Plate DOE

Table E1 Top Plate DOE results

Variable Actual values						
	low (-1)	high (+1)	units			
Material	40	50.7	Kpsi			
Lip Thickness	0.3	0.4	in			
Lip Width	1	1.25	in			

			Material	Lip thickness	Lip Width		
		I	x3	x2	x1	d1d3	mm def.
1	Al, thin, narrow	1	-1	-1	-1		0.338
2	Al, thin, wide	1	-1	-1	1		0.34
3	Al, thick, narrow	1	-1	1	-1		0.264
4	Al, thick, wide	1	-1	1	1		0.266
5	St, thin, narrow	1	1	-1	-1		0.113
6	St, thin, wide	1	1	-1	1		0.178
7	St, thick, narrow	1	1	1	-1		0.088
8	St, thick, wide	1	1	1	1		0.088

Resultant ß's	0.209375	-0.0926	-0.032875	0.008625

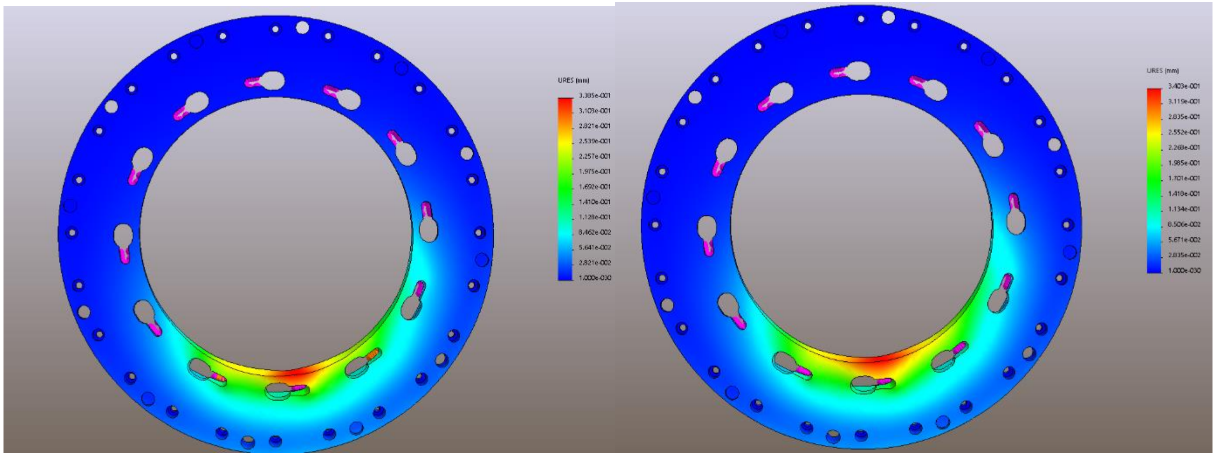


Figure E1 Variants 1 and 2 respectively

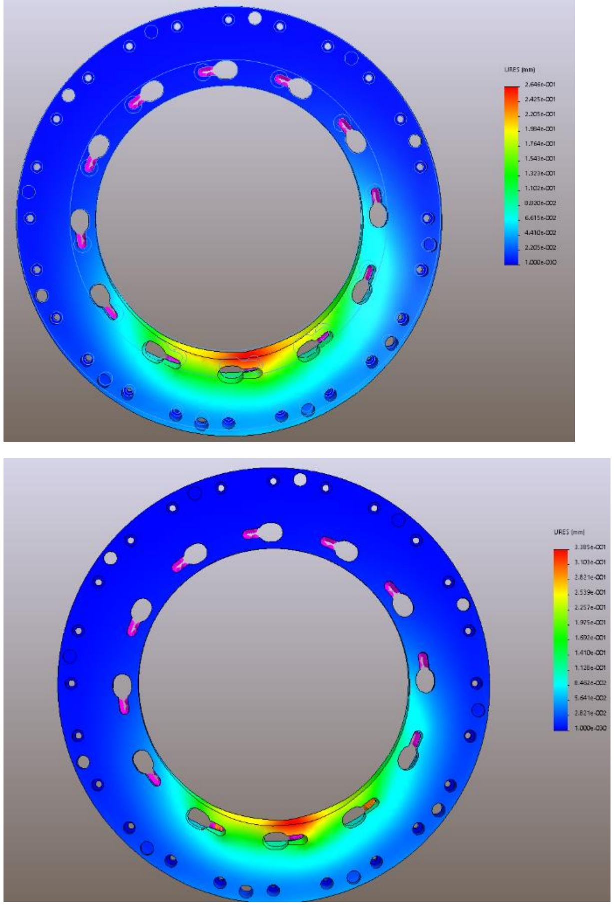


Figure E2 Variants 3 and 4 respectively

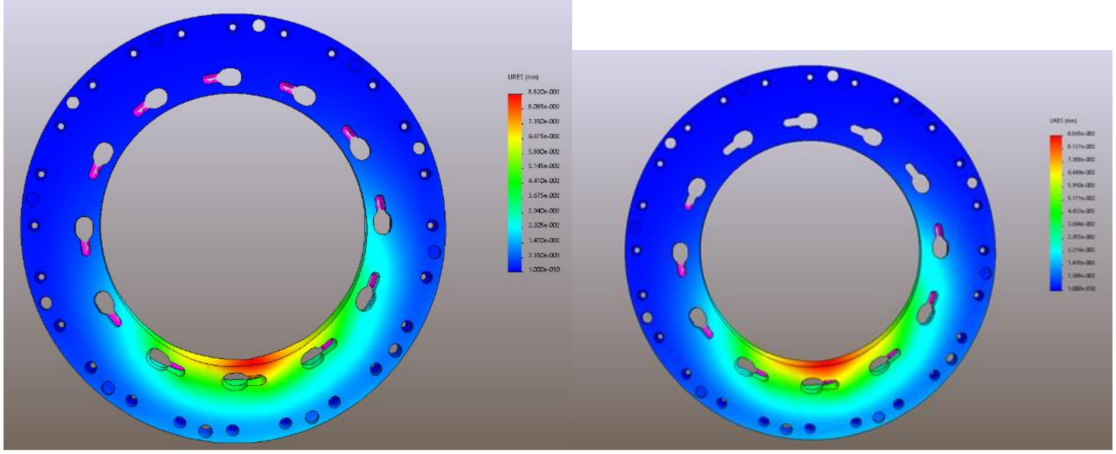


Figure E3 Variants 5 and 6 respectively

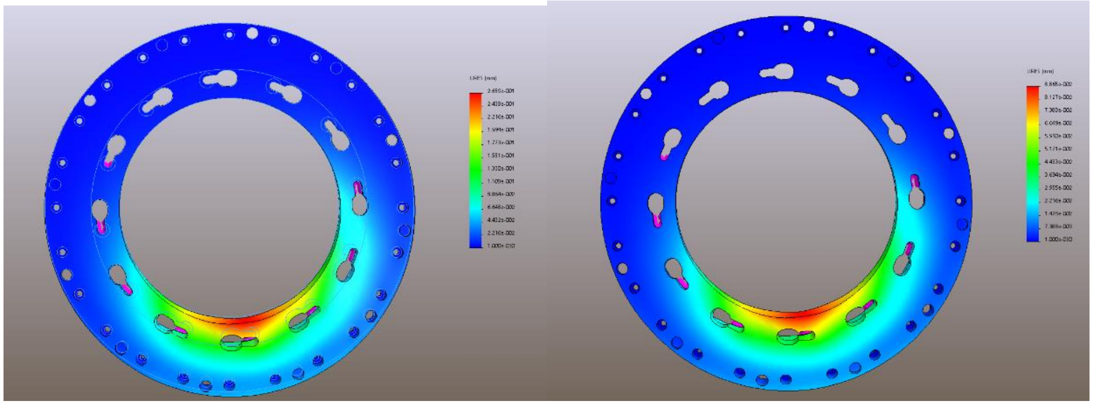


Figure E4 Variants 7 and 8 respectively

Appendix F: Bottom plate DOE results

Table F1 Bottom plate DOE results

Variable Actual values

	low (-1)	high (+1)	Units
Material	40	50.7	Kpsi
Base Thickness	0.3	0.4	in
Wall thickness	0.75	1	in

			Material	Base Thickness	Wall Thickness		
		I	x3	x2	x1	d1d2d3	Displacement (mm)
1	Al, thin, narrow	1	-1	-1	-1		0.444
2	Al, thin, wide	1	-1	-1	1		0.526
3	Al, thick, narrow	1	-1	1	-1		0.213
4	Al, thick, wide	1	-1	1	1		0.255
5	St, thin, narrow	1	1	-1	-1		0.153
6	St, thin, wide	1	1	-1	1		0.182
7	St, thick, narrow	1	1	1	-1		0.074
8	St, thick, wide	1	1	1	1		0.009

Resultant ß's	0.232	-0.1275	-0.09425	0.011

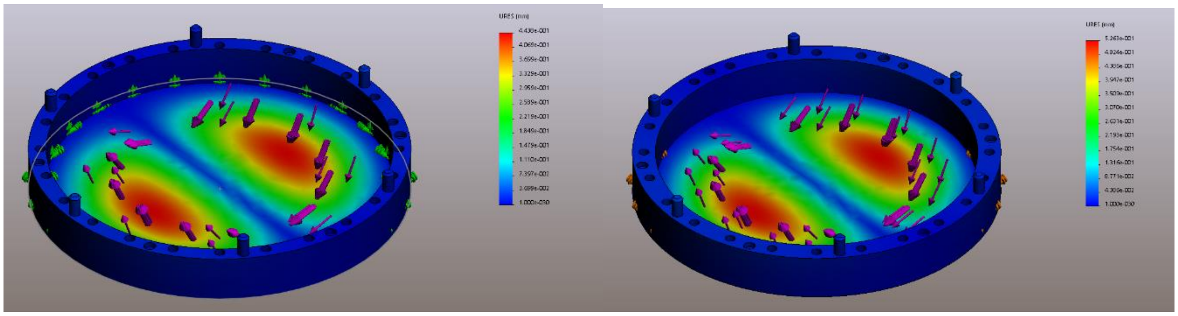


Figure F1 Variants 1 and 2 respectively

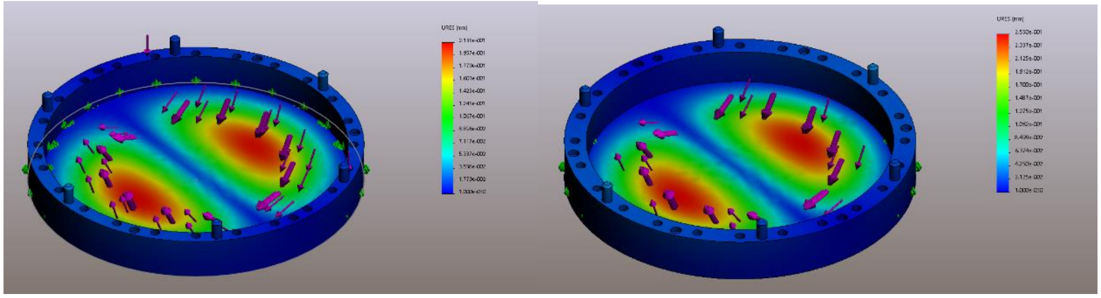


Figure F2 Variants 3 and 4 respectively

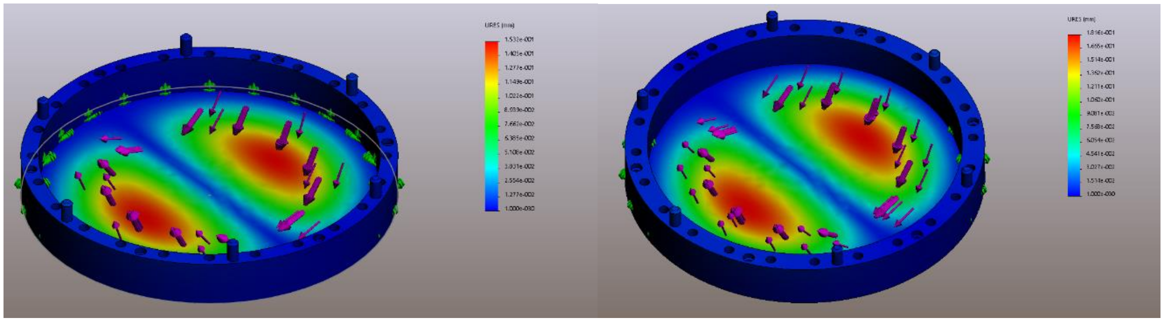


Figure F3 Variants 5 and 6 respectively

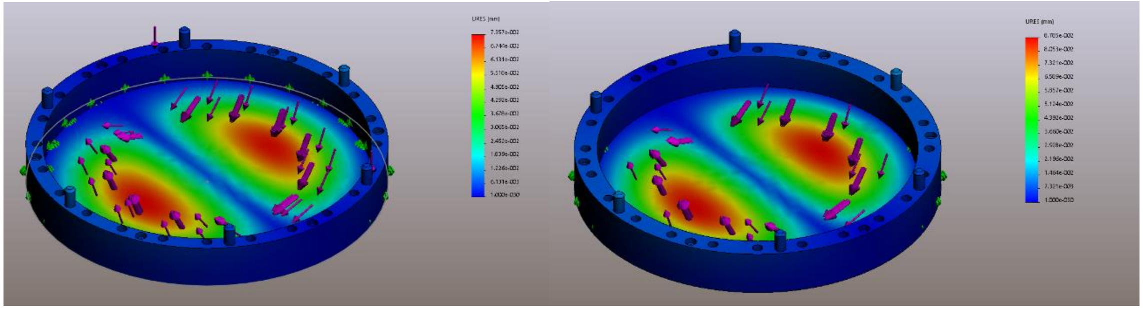


Figure F4 Variants 7 and 8 respectively

Appendix G: Factor of Safety

Table G1: Project Requirements with Factor of Safety

Item	**Stress (lbf/in^2)**	**Critical Stress (lbf/in^2)**	**Factor of Safety**
Ring (axial + bending) Buckling Stress	40,000	5,139,620	128
Ring (axial + bending) Distributed Over Area	1,057	40,000	38
Ring (axial + bending) Coupled	2,340	40,000	17
T-Hooks (flange)	2,908	40,000	14
T-Hooks (distance X=5.6)	**13,990**	**40,000**	**2.86**
T-Hooks (distance X=4.8)	5,092	40,000	7.86
T-Hooks (distance X=2.8)	3,492	40,000	11.45
T-Hooks (large shaft)	7,136	40,000	5.61
T-Hooks (small shaft)	**13,980**	**40,000**	**2.86**
T-Hook (head)	36	40,000	1,100
Alignment Pins	1,038	40,000	39