FINAL DESIGN REPORT

ARTICULATING BACKPACK SPINE

Wolfpack Gear, Inc.

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EXECUTIVE SUMMARY:

In the field, firefighters and Urban Search and Rescue (USAR) personnel need to transport variable loads efficiently, safely, and comfortably while simultaneously performing certain physical tasks. Current models of external and internal framed backpacks distribute the load of a pack efficiently, but do not allow for the natural movement of the wearer. Wolfpack Gear, Inc. proposed the need for a system which both effectively carries a load and allows for the unhindered natural movement of the user. The goal of this project was to design, build, and test an articulating backpack support system. The first stage of the project comprised of the groundwork necessary to establish a design concept: defining the problem, outlining the scope of the project, researching the current market and patents, and completing an extensive brainstorming and ideation phase. The second quarter of the project focused on turning the proposed concept into a concrete design through engineering analysis, extensive solid modeling, and initial prototyping. The final phase of the project was to construct a functional prototype that was then tested and iterated upon.

CHAPTER 1: INTRODUCTION

In the line of duty, it is necessary for firefighters to be able to carry out a wide range of physically demanding tasks that require an assortment of different equipment. When out fighting wildfires, firefighters have to carry all of their gear to sometimes remote locations with varied terrain. This gear can range from just a canteen of water to 50 pounds of hoses, creating a need for a pack that is as versatile as the jobs to be done. Fighting fires is already a very physically demanding task, so it is important that firefighters are able to get from point A to point B with as little fatigue as possible. Mike Oberndorfer, a current Fire Captain, started Wolfpack Gear, Inc. in 2002 to meet the unique needs of firefighters by designing from the point of view of one. Since then, Wolfpack Gear has been designing packs for firefighters and Urban Search and Rescue personnel with the mission of creating gear that combines safety, comfort, and strength.

1.1 PROBLEM DEFINITION:

Wolfpack Gear came to our group with the goal of designing a support system that could be easily assimilated into their current line of packs. The objective was to design an articulating spine that will stiffen under a heavy load, but will also be flexible enough to accommodate a light load with maximum comfort and maneuverability. In order to increase the versatility of the system, we decided to fabricate the spine out of carbon fiber to minimize the overall weight while maintaining the strength and rigidity. A lightweight and versatile design was important in order to be able to easily incorporate the spine into Wolfpack Gear's current backpacks or even a firefighter's jacket later down the road.

Our team worked very closely with Wolfpack Gear to ensure that the quality of the project was consistent with Wolfpack Gear's high standards. Our team worked directly with the Engineering Design Coordinator, Myles Wittman.

1.2 MANAGEMENT PLAN:

In order to improve our efficiency as a team, we assigned each member a focus area. We believed that this would best support the strengths of each team member and would ensure that all areas of the project were given appropriate attention. All team members will be involved in accomplishing all aspects of the project. Areas not covered by these three categories will be shared responsibilities by all members. Examples include solid modeling, calculations, and testing. The positions are detailed below.

1. Communications Officer: Salvatore Monforte
    a. Acts as the main point of communication with the sponsor
    b. Facilitates meetings with the sponsor

2. Manufacturing Officer: Savan Patel
    a. Oversees the production of parts and assemblies
    b. Handles the specifying and ordering of parts and materials

3. Ideation Officer: Darci Lawrence
    a. Keeps track of design concepts and ideas in a well-organized manner
    b. Connects the group's research to specific ideas and vice-versa

To keep track of deadlines throughout the project, we created a Gantt Chart, and then later a Smart Sheet. The Gantt Chart and Smart Sheet shown in Appendix E, highlight the project milestones and outlines the dependency of various steps throughout the project.

CHAPTER 2: BACKGROUND

2.1 BACKGROUND RESEARCH:

Currently on the market, there are packs designed for heavy loads and light loads, but few that are able to cross over between the two. The two main types are internal and external frame backpacks. External frame packs are commonly used for heavy load applications such as backpacking and hiking. An example is shown in Figure 1. They usually feature a rigid aluminum frame that supports the heavy load of the pack and focuses the majority of the weight on the wearer's hips using a padded waist belt. With external frame backpacks, the heavier portion of the load is usually stored towards the top of the pack, which can sometimes lead to the wearer feeling off balanced or top heavy. Additionally, the rigid frame is generally bulky and not very accommodating for lighter loads.

Figure 1. External Frame Backpack [5].

Figure 2. Internal Frame Backpack [6].

In contrast to the external frame, the internal frame is better suited to also accommodate lighter load applications. These backpacks, shown in Figure 2, generally feature a semi-flexible frame incorporated into the wall of the backpack. The frame is usually made of a combination of flexible plastic sheets, padded blocks, and sometimes in the more heavy-duty packs, flexible aluminum or graphite stays. In these backpacks, the majority of the weight of the load is stored lower in the pack, which allows for greater maneuverability for the wearer. Similar to the external frame, the majority of the load is focused on the hips through a padded waist belt.

After conducting a patent search, we found several different interpretations on the articulating backpack support. Quite a few of the designs featured a mostly rigid frame with a pivot point at the top and bottom of the frame to allow the hips and shoulders to rotate freely. This is important because most people walk with the opposite arm and leg forward and are thus limited in motion by the rigid frame of most standard backpacks. Consequently, the pivot points allow for a more natural walking motion. An example of this is shown in Figure 3.

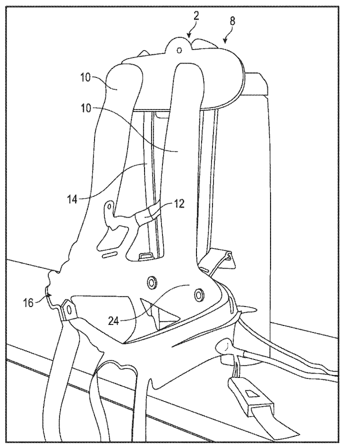

Figure 3. Backpack support with shoulder and hip pivot points [7].

With further research we found a carbon fiber backpack support that had a series of curved supports used to disperse the weight of the load in order to minimize the load carried by the shoulders. Shown in Figure 4, this design also featured a pivot point at the hips to allow the wearer to maintain a more natural gait.

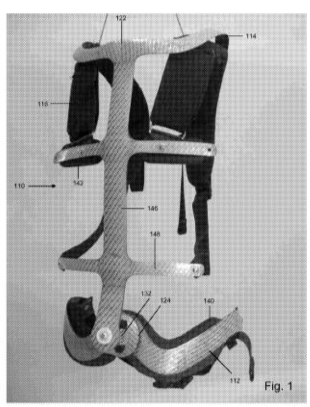

Figure 4. Carbon fiber rigid support with pivot [4].

In contrast to the more rigid frames, one design we found features flexible webbing attached to a more rigid structure. It functions similar to a suspension bridge with the webbing being supported in tension as can be seen in Figure 5. Not only does the webbing help to better distribute the load, but it also allows the backpack to better conform to the shape of the back for increased user comfort.

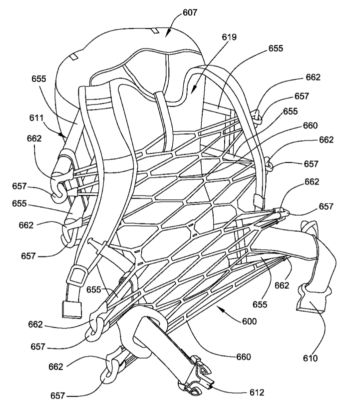

Figure 5. Tensioned flexible back support [2].

The backpack shown in Figure 6 was also found during our patent search. It features a frame made from one continuous element that forms three closed loops. This design was interesting to us because of its ability to improve mobility in each of the three categories that we defined: lateral movement, bending, and twisting. This design also inspired several of our design concepts in that it was able to be exceedingly innovative, but also relatively simple.

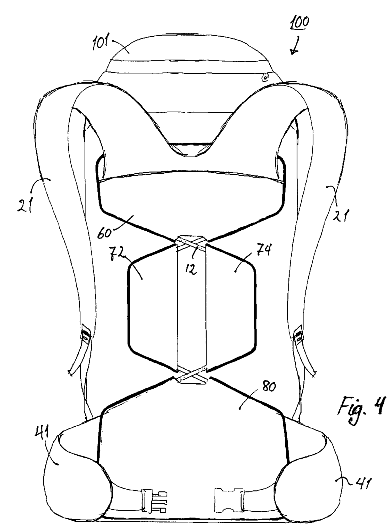

Figure 6. Bergans Glittertind Pack [3].

Our patent search resulted in several noteworthy conclusions. First off, there is no currently patented, fully articulated, segmented backpack frame. Also, the volume and diversity of current designs provided numerous ideas and inspirations for the group to take into brainstorming.

In addition to the patent search, we also investigated the quality and safety standards that Wolfpack Gear is committed to providing to their customers. They earned the ISO 9001 Certification in 2006, which sets a minimum standard of quality requirements that a company must adhere to. Additionally, their products are evaluated and certified under the UL certification for specific standards for flammability and heat resistance as specified by NFPA 1977, 2005 edition [8]. Our team worked closely with Wolfpack Gear to ensure that our designs adhered to these same standards.

2.2 REQUIREMENTS AND SPECIFICATIONS:

Based on a list of requirements provided by our sponsor, which can be found in Appendix A, we created a set of design specifications that have been used to validate potential designs. This list of design specifications can be seen in Table 1 on the next page. The primary objective and main scope of this project, as defined by our sponsor, was to create a backpack support system that can be integrated into Wolfpack Gear's already existing line of backpacks. The support system must be able to move freely with the user when un-weighted, and when loaded, the system must stiffen in order to distribute the weight safely and comfortably. Additionally, the system needed to be size efficient and low profile. Because the strength to weight ratio of the structural components was essential to the success of the design, we decided to utilize carbon fiber.

From this initial set of requirements, we created a Quality Function Deployment (QFD) model using the House of Quality method, which can be seen in Appendix A. This model broke down the customer requirements into a set of quantitative engineering specifications. Further, this model allowed us to develop relationships between individual engineering specifications in order to gain a better understanding of how the requirements would affect each other. Each specification was also given a score on a scale of 10 to determine its overall importance to the design from the perspective of the anticipated customers: Wolfpack Gear, firefighters, and the general public.

To parameterize the requirements, we decided on thirteen main engineering specifications, which are listed in Table 1. We chose parameters of length, width, and system weight to address the size requirements. Additionally, the load bearing and shoulder load specifications dealt with the customer requirements for loading and load distribution. To tackle the requirements of mobility and flexibility, we chose two movement parameters that established a desired range of motion for back flexion and extension as well as rotation. Another important specification was the minimum heat that the material could withstand. This was chosen to adhere with Wolfpack Gear's current standards for material selection. Other parameters that were more difficult to quantify numerically, but that we still found important to consider in the design process were safety, wearability, cost, reliability, and lifetime. Safety and reliability were definitely at the forefront of all design considerations, but were difficult to quantify in the initial design stages and were explored further during the construction and testing of the prototype. In order to ensure comfort and performance over a long period of continuous use, wearability was an important quality to consider. We parameterized lifetime at greater than 10 years, but we also needed to consider that the backpack will be used in extremely rugged conditions and will therefore take on additional wear and tear.

Another requirement of the design was that it needed to be able to easily attach to Wolfpack Gear's existing line of packs with minimal modification. In order to accomplish this, we designed our pack around Wolfpack Gear's current standard for pack attachment. By having almost all of our materials supplied directly by Wolfpack Gear, we were able to ensure that our design would adhere to the aforementioned material temperature standards.

Table 1. Wolfpack Gear Articulated Backpack Spine Formal Engineering Requirements.

Spec #	Parameter Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Weight	≤3 lbs.	MAX	M	A, T
2	Length	16-23 inches	±2 inches	M	A,T,S
3	Width	≤18 inches	MAX	M	A,T,S
4	Load Bearing	≥75 lbs	MIN	H	A,T,S,I
5	Shoulder Load	≤15 lbs	MAX	H	A,T,S,I
6	Flexion/Extension	45 degrees	±5 degrees	H	A,T,I
7	Rotation	80 degrees	±5 degrees	H	A,T,I
8	Material (temp.)	≥450 °F †	MIN	H	A,T,S,I
9	Safety	100%	-	H	A,T,S,I
10	Wearability	≥10 hrs cont.	MIN	H	T,S
11	Cost	*	*	L	A,T,S,I
12	Reliability	100%	-	H	A,T,S,I
13	Lifetime	≥10 years	MIN	H	T,I

* Note: no specific cost parameter was given. Cost parameters will be determined based on the viability of the product.

† In order to meet the temperature requirement, the design must be able to withstand a temperature of 450°F for 5 minutes to stay consistent with Wolfpack Gear's standards.

The symbols for the table are explained as follows:
A- Analysis
T- Testing
S- Similarity to existing designs
I- Inspection
H- High
M- Medium
L- Low

CHAPTER 3: DESIGN DEVELOPMENT

3.1 CONCEPT GENERATION:

Once we defined our problem, established our design specifications, and completed our preliminary research, we began our ideation phase. To help organize our brainstorming process, we divided our design problem into two main components. Ideas were classified by whether they dealt with flexibility and facilitating the natural movement of the system or whether they were structural and dealt with supporting the load of the pack. Once we had a clearer understanding of the requirements of our overall design, we began to brainstorm ideas. Because our project was fairly open ended with multiple possible solutions, we wanted to come up with as many ideas as possible. Therefore, we utilized several different brainstorming methods in an attempt to get as creative as possible.

Initially, we created a list of functions and attributes, which supported the two previously mentioned main concepts. From these lists, we wrote down the ideas that could potentially meet the needs of these functions and attributes on sticky notes. To avoid any negative judgment, ideas were first written down individually and then all of the ideas were brought together. We then broke up the ideas into groups based on similarity. From these groups, different combinations of ideas were mixed and matched as our design conversations continued. After a period of incubation, the team met again and displayed all of the sticky note ideas on a whiteboard. Each team member then took a turn presenting different combinations of ideas as well as explaining specific concepts they brainstormed. Through this process, variations of different ideas arose and were recorded in the team's logbooks.

3.2 INITIAL CONCEPTS:

Once we felt that we had exhausted all the brainstorming that we could, we created a list of feasible concepts that could potentially be chosen for further consideration. Although our actual final design was not included in this initial list, it was the process of analyzing these ideas that ultimately led us to the concept presented in the preliminary design review. Due to the pure design nature of our project, the brainstorming process was integral to our design process. While we did lay out a series of specific design requirements, many aspects of our design could not be judged solely by numerical parameters. Therefore, we found that the exploration and thorough discussion of different concepts was the best way to determine how various aspects of these designs would work. This next section of the report details the designs that were used in our decision-making process and discusses the positive and negative aspects of each design.

Ball and Socket Joints

Looking towards the human body for inspiration, the ball and socket concept embodies the joint design found in our shoulders. The individual segments are joined through a ball and socket joint that allows for a high range of rotational and lateral movement. Once the ball and cup are in contact, an impression in the cup inhibits movement to a certain extent and allows the joint to stiffen up when loaded. In order to be more space efficient, we decided that the joint could be flattened slightly and made more planar, so essentially, it would be more of an "oval in socket." While the planar ball and socket would have a more limited range of motion than a standard ball and socket, we felt that this concept still met the movement requirements for our project. The backpack spine joints do not require the same extent of rotational movement as our shoulders. Figure 7 shows a crude mockup of the joint. The rubber bands represent a cable that that could be pulled to stiffen the joint manually. This design seemed to facilitate a great deal of motion, but we were unsure if it would be able to withstand the necessary axial loading when the pack weight was increased.

Figure 7. Mockup of ball and socket joint stiffened (left) and relaxed (right).

Sliding Plates

The sliding plates concept was also inspired by the human body, but this time by the vertebrae in the human spine. It incorporated a set of complementary shaped segments that rest on top of each other and are able to slide along their contact surface. The pieces are held together by a semi-elastic central "spinal cord." Throughout the brainstorming process, the team considered different shapes and sizes for the individual segments and felt that if the design was to be continued further that the shape and size could easily be modified following additional prototyping and analysis. Figure 8 shows two versions of the sliding plates. We originally started with the idea of the squared interlocking plates but found that the rounded one offered more lateral movement since the plates could slide easily along the curved surface. The straws in these mockups were threaded with a rubber band and acted as the semi-flexible spine. As mockups, these designs demonstrated the segmented movement that was desired. However, when considering how the system would be loaded axially, we realized that the plates would need to align perfectly in order to properly distribute the load along the spine. In order to address this, we decided that the contact surfaces would need to be slotted in some fashion, which would consequently restrict the flexibility of the design. Another potential issue that we foresaw in this design was whether or not the constant rubbing and sliding between the plates would be detrimental to the structural integrity of the plates and thus drastically affect the lifetime of the parts.

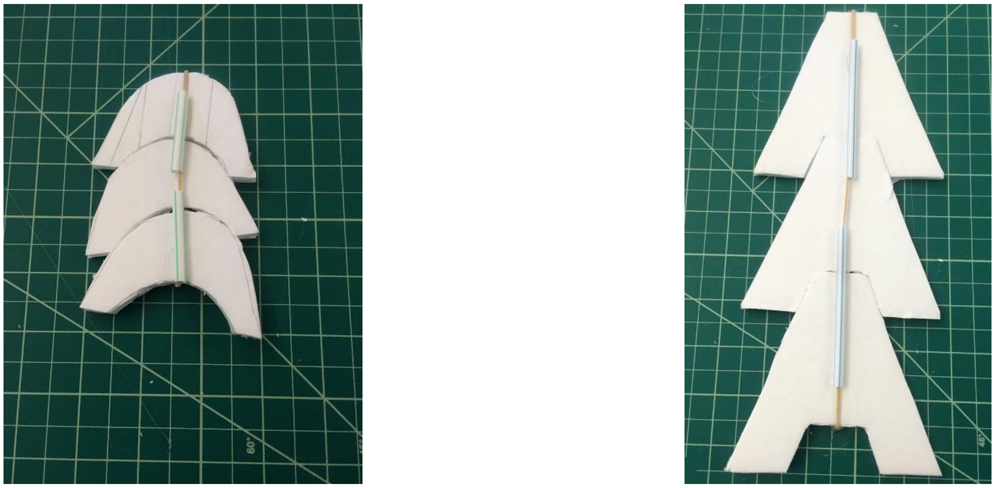

Figure 8. Mockup of sliding plates concept.

Springs and Sliders

A slightly more mechanical design, the springs and sliders idea relied on a set of semi-flexible tracks and a fair amount of user input. In this design each panel is connected to the panel above and below by a pair of springs, and the segments are all held in place by a set of semi-flexible tracks that run along the outside edges of the pack. Flexion and extension will be facilitated as the segments move vertically along the tracks. Rotation and lateral movement will be achieved as the segments move, ever so slightly horizontally, which is made possible by slotted holes where the segments attach to the tracks. Between the segments, there is a set of two springs, each located near the tracks along the outside of the apparatus. These springs hold the segments away from each other when the pack is un-weighted and allow for ample movement of the plates. Running vertically along the center of the spine, a cable system will be used to pull the plates into contact with each other to stiffen up the spine. The cables will be tightened when the user pulls on a cord positioned at the bottom of the spine system.

This system was a bit more complicated than the previous designs due to the fact that it had more moving parts. Another concern with this idea was that it had several areas of possible failure, which therefore put the reliability and lifetime of the system into question. Additionally, to provide the weight bearing rigidity needed, the segments need to correctly come into contact with each other. To ensure this proper alignment, we felt the tracks would have to be stiffer than we would like. Having two fairly rigid tracks running the length of the back significantly limited the overall flexibility of the system. The more we thought about this idea, the more it turned into an internal frame backpack with an unnecessary amount of moving parts in the middle of the pack.

The mockup in Figure 9 demonstrates the springs and sliders idea. The rubber bands represent the cable system, while the short lengths of toothpicks represent the springs that would reside in between the segments. The tracks are not present on this mockup, but would run in a semi-curved fashion along the outside edges of the segments.

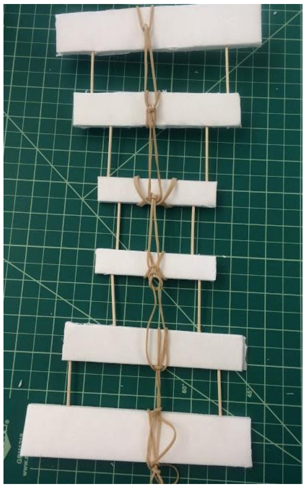

Figure 9. Mockup of springs and Sliders

This idea did, however, lead us into a discussion about how to define the movement of our segments and also posed the question of how much of that movement needed to be defined in order to transmit the load of the pack effectively.

Imitation Spine

Similar to our own spine, this concept involved a column of hard segments, with softer flexible pieces set between them. The segments, along with their flexible counterparts, would be constrained either within some sort of sheath or strung axially along a cable of some kind, similar to our own spinal cord. The segments could be individually shaped and sized depending on the movement intended for each one and the location of that particular segment on the back. The main problem that arose when brainstorming on this idea was in finding a soft material that could be used between the segments. Due to the intensive heat and wear requirements of the project, we decided that it would be too difficult to find a suitable material that would still allow for the movement and flexibility of the system while also meeting our specifications.

"Bamboo Mat" Concept

During one of our later brainstorming sessions, in an attempt to come up with a different method of defining the movement of segmented parts, we came up with what we called our "bamboo mat" concept. We gave it that name because it was originally inspired by the commercially manufactured bamboo mats that are used as placemats or to roll sushi. We liked the idea of how in a bamboo mat the individual bamboo panels can work both on an individual level and as a cohesive unit. Because of the way the bamboo slats are held together with string, they are able to act both as a single flat mat and also are allowed to bend relative to each other to the point where the mat can be rolled up. Translating this idea to match our application, we developed a system of slats that move in relation to each other and to a solid base plate. The base plate is to be stiff enough to control the movement of the plates but still flexible enough to move with the user. The base plate is not weight bearing but rather guides the slats as they come together and stiffen up and also serves to isolate the moving slats from the user. The shoulder straps and waist belt are attached to the plates themselves along with the load. As the load is increased, most of the weight is directed down the system to the bottom plate, which is attached to the waist belt. Figure 10 shows a sketch of this concept.

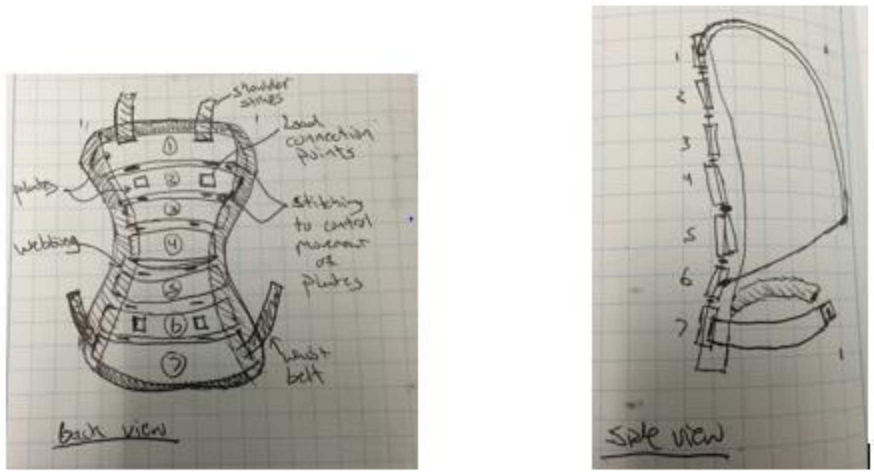

Figure 10. Back and side views of the Bamboo Mat concept

Independent Suspension

Similar to the tracks and sliders concept mentioned earlier, the independent suspension concept is built around two semirigid supports that run along the sides of the user's back. Between these suports, a set of segments is independently suspended. The segments are configured in a way so that when the system is unweighted, they are free to move in almost any direction, allowing for comfortable movement of the user. When the segments are loaded, the suspension is designed for the segments to align in a structural manner. This design was enticing at first, as it appeared to allow a great amount of movement and provide a smooth mechanism for stiffening. However, more consideration led to a similar conclusion as with the springs and sliders concept. In order for the segments to bear the load, the rods that support the segments would have to be stiffer than desired for our application. Once again, as the supports are forced to get stiffer, the concept becomes nothing more than an unessesarily complicated version of an internal or external frame backback. The mockup pictured in Figure 11 shows this concept. The rubberbands illustrate some type of elastic polymer or fabric.

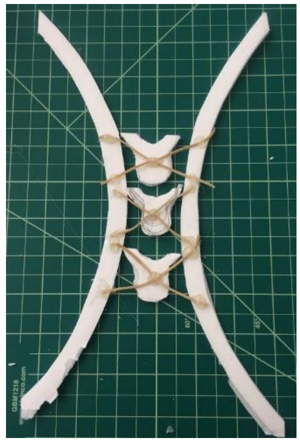

Figure 11. Independent Suspension Conept.

Window Blinds

The window blinds concept is an offshoot of the bamboo mat idea. Rather than have the slats or plates slide relative to the flexible base material, the plates are fixed to the fabric. As the segmented plates move relative to each other, the base material folds over itself, similar to fabric window blinds. We were drawn to this design because of how simple the mechanism is to switch between the flexible and rigid state. However, we were concerned that in the stiffened state that a majority of the load would be taken by the base material and not the structural segments as intended. In essence, the backpack would act like a regular frameless pack.

Three Panel Pivot

Taking inspiration from the Bergans Glittertind Pack, mentioned in the Background section of the report, this design revolves around a three panel design with two pivots. The load is attached to the system through the pivot segment and the weight is distributed through a large contacat area existing between the pivot segment and the hip segment. The shoulder and hip segments are slotted to allow momement both vertically and lateraly between the segments. Because there was a great deal of initial interest in pursuing this idea, prototypes were made out of both cardboard and wood to roughly test if the movements being conceptualized were realistic. After building the prototypes and performing simple movement tests, we determined that the design failed to provide the full range of motion that we were expecting. Figure 12 shows a labled sketch of the three panel pivot concept and a picture of our wood prototype.

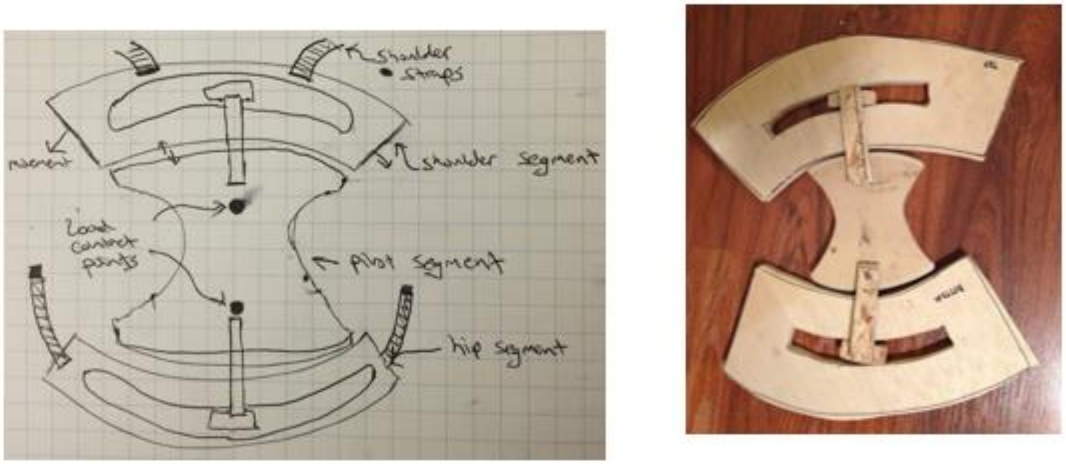

Figure 12. Three panel pivot sketch (left) and wood prototype (right).

3.3 IDEA SELECTION:

Because our brainstorming process was so extensive, our idea selection process also took a significant amount of time. Our first step towards selecting a design was to break down the concepts that we brainstormed into a concrete list of distinct ideas. We created a list of 10 different ideas and labeled them A through J. A brief description of the concepts and their labels are listed in Table 2.

Table 2. List of design concepts and their labels.

Label	Concept Description
A	Flattened ball and socket joint
B	3-D Ball and socket joint
C	Rounded sliding vertebrae
D	Interlocking Square Vertebrae
E	Springs and sliders
F	Imitation spine
G	Bamboo mat concept
H	Independent suspension
I	Bamboo mat with folding blinds concept
J	3 Segment pivot

From this list of possible designs, we eliminated several ideas based on a go/no go evaluation. Designs that were given a "no go" label were deemed too complicated or did not properly meet the design specifications. Idea B was deemed "no go" because the team believed that a 3-D ball and socket joint would be too bulky and did not meet the desired slender design. Concept D was also given a "no go" because we felt that it was too fixed and thus did not provide enough movement to meet the flexibility criteria. Another concept that did not pass the go/no go test was idea H because it was too complicated of a design to be a practical solution to our problem.

Once we eliminated these concepts, we put the remaining concepts into a Pugh Matrix, which can be found in Table 3 and 4 in Appendix A. A Pugh Matrix is a decision making tool that compares competing designs against a datum. The designs are either given a positive or negative sign for a specific design criteria based on whether they perform better or worse than the datum. To judge the different designs, we came up with a list of 12 design criteria, which can be seen in Table 5. The first six criteria, 1a through 3b, address the flexibility of the system. Rotation was classified as twisting about a vertical axis, lateral movement as moving in an arc side to side, and flexion/extension as bending forwards and backwards. Load distribution referred to how well the design was able to distribute the majority of the weight from the shoulders to the hips as specified by the customer requirements. Simplicity designated the overall feasibility of the design based on the complication level of the concept or the number of moving parts. In order to meet the specifications for a lightweight design, we judged our concepts based on the anticipated overall weight of each design. Since our design needs to be as minimalistic as possible, we chose space efficiency to classify the perceived bulkiness of the design. Loaded stiffness referred to the rigidity of the system under heavy loading. Finally, transitionability was used to classify how well the designs were able to crossover from a high load to a low load application.

Table 3. Design criteria for Pugh Matrix and Decision Matrix.

Label	Design Criteria
1a	Loaded rotation
1b	Unloaded rotation
2a	Loaded lateral movement
2b	Unloaded lateral movement
3a	Loaded flexion/extension
3b	Unloaded flexion/extension
4	Load distribution
5	Simplicity
6	Backpack weight
7	Space efficiency
8	Loaded stiffness
9	Transitionability

In the first Pugh Matrix, Table 3 in Appendix A, we evaluated the ideas using an existing internal frame backpack as the datum. The Pugh Matrix resulted in a three-way tie between the rounded sliding vertebrae and the two bamboo mat concepts. It also showed that the flattened ball and socket joint had the most criteria that were less satisfactory than the datum, and the springs and sliders and the imitation spine concepts had the least amount of areas that exceeded the internal frame backpack. However, no design stood out from this process as either the best or the worst, so we decided to create another Pugh Matrix, Table 4 in Appendix A, using the rounded sliding vertebrae concept as the datum. This matrix we found to be even less conclusive with almost all of the designs scoring very similarly.

Although the Pugh Matrix didn't end up being extremely useful to us in terms of idea selection, it did help us to generate new ideas. The Pugh Matrix illustrated the points of strength and weakness of each of the design concepts. From this, we began to combine different aspects of each design to create new concepts entirely.

In order to achieve some more decisive results we decided to make a weighted Decision Matrix. We used the same list of concepts and design criteria as the Pugh Matrix, but this time gave each criterion a weight based on its perceived importance to the overall design. Additionally, each design concept was rated on a scale of 1 to 100 on how well it met the design criteria. Our Decision Matrix can be found in Appendix A.

Our first realization in the Decision Matrix was how difficult it was to quantify our design criteria which we felt were much more subjective than originally anticipated. Because of this, we realized that there was some disagreement between team members on how well a certain design was able to meet the design criteria. Further, this showed how for some of the design concepts, each team member had a slightly different understanding of what the concept actually was. Therefore, we decided it was important to draw more detailed sketches and create as many physical mockups of these concepts as possible in order to clarify exactly what each design concept entailed. Once we had a clearer picture of each design, we were able to go back and finish evaluating with the Decision Matrix.

From the Decision Matrix, we saw that two of our designs scored higher than the others. The highest scoring design was the bamboo mat concept, and the second highest was the three panel pivot. Since the two scored very close to each other, we decided to pursue each of these designs further before a final decision was made. An important step in our decision making process was to make a mockup of each design. As previously discussed, once we built a mockup of the three-panel pivot, we realized that the design did not achieve a great enough range of flexibility. Even though our mockup of the bamboo mat concept was incredibly crude, having been made out of paper bags and cardboard, it was enough to visualize the concept. From the mockup we realized that the bamboo mat concept was not only a feasible means of achieving our goal, but it was also an incredibly simple overall system. Therefore, we decided to proceed forward with the bamboo mat concept.

3.4 PRELIMINARY DESIGN IDEA:

The concept that we decided to move forward with for the Preliminary Design Review actually combined the two bamboo mat concepts that we discussed previously. The design features a set of rigid panels that are able to interlock because of their offset geometric shape as shown in Figure 13. The movement of the panels is restrained to the plane of the flexible back plate by two sleeves that hold the ends of each panel in place against the back. The segments are free to slide within the sleeve in the vertical direction between their relaxed state and compressed state. The shoulder straps attach to the flexible back plate, but are not directly attached to the load. The load is attached to the top slat, so that as more weight is added, it forces the panels to interlock and form a load bearing and rigid spine. Since the load is not actually attached to the shoulder straps, and due to the fact that the slats slide down when weighted, the majority of the load will be distributed to the hip plate and ultimately, the hip belt. On the side of the panels that isn't sliding on the flexible back plate, the slats will be connected with fabric in a fashion similar to the window blinds concept. In the relaxed state, the fabric will be essentially flat, but when the panels interlock, the fabric will fold upon itself. An elastic strap attached to the top panel will pull the panels back apart in the unloaded state, thus separating the segments and allowing for maximum flexibility. An isometric view of our concept is shown in Figure 14.

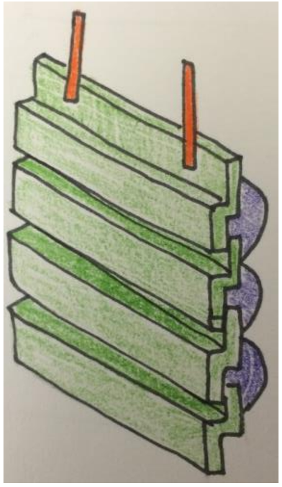

Figure 13. Offset interlocking panels.

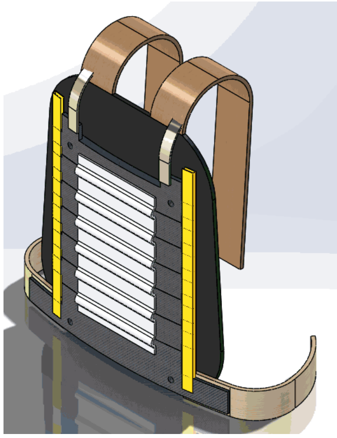

Figure 14. Isometric view of the Bamboo Mat backpack design.

Although the original bamboo mat concept featured flat panels, similar to those shown in Figure 13, we have decided to give the panels a slight curvature to increase the overall flexibility of the system. With the curved panels shown in Figure 15, we will be able to achieve rotation through the panel's ability to slide along their matching curved surfaces. There will be a little extra room in the sleeves to accommodate for this movement. We believe that this will significantly increase the overall flexibility and comfort of the system.

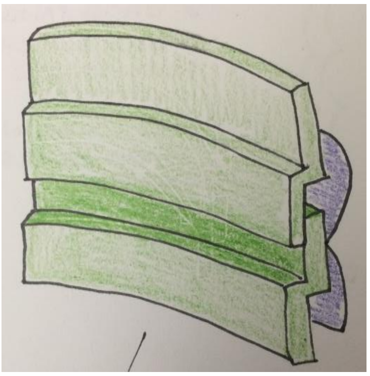

Figure 15. Curved panels and fabric attachment.

Solidworks Models of Preliminary Design:

After we selected our design, we created a 3D model using Solidworks to show the different parts needed in the assembly. An exploded view, shown in Figure 16, shows the basic parts involved in the assembly. Items not shown in the assembly are the straps and buckles used to fasten the backpack to a person. In the model, the loading is attached to the top slat and is transferred through the intermediate slats to the bottom slat where the weight is then transferred to the hips through a waist belt. The shoulder straps undergo minimal loading because their purpose is to constrain the backpack to a person.

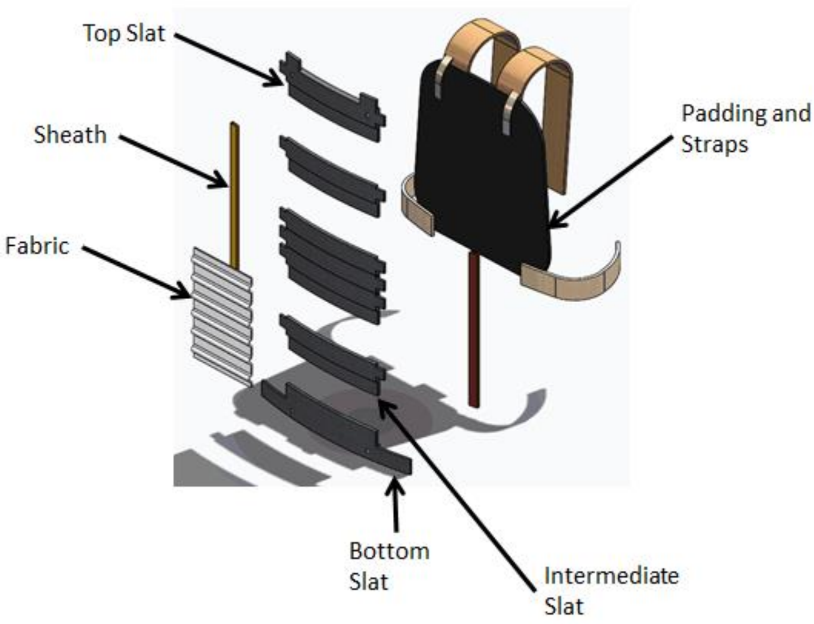

Figure 16. Exploded view of the Bamboo Mat backpack design.

Analysis of Preliminary Design:

In our rough Solidworks model, we considered different material such as 6061-T6 aluminum, 1020 carbon steel, and carbon fiber. The maximum stress as well as the yield strength and weight of each component are shown in Table 6. The top slat showed the largest stress because the two loading points support a vertical load and a moment because of its current design. All of the slats are well below the yield strength proving that our design will satisfy the criteria and can be optimized to further reduce weight.

Table 4. Slat material and strength analysis

Material	Yield Strength	Top Slat		Middle Slat		Bottom Slat	
		Mass (Kg)	Max Stress (MPa)	Mass (Kg)	Max Stress (MPa)	Mass (Kg)	Max Stress (MPa)
Carbon Fiber	570 MPa	0.33	30.47	0.28	2.01	0.32	2.34
Aluminum 6061-T6	275 MPa	0.56	28.82	0.38	1.91	0.54	2.23
Steel 1020	351 MPa	1.63	29.21	1.10	1.92	1.58	2.22

One of the main benefits of this design is that it is overall a very simple concept. The interlocking plates are basic geometric shapes that will be easy to mold and layup in carbon fiber if we decide to use that material. Additionally, because of the simplicity of the design, there is ample room for possible design iterations and improvements later on down the road. For example, we can design and test different shaped plates and also an assortment of different sized plates with minimal changes to the overall design concept. Therefore, we believe that this design offers the most benefits in terms of its simplicity, and is also the best suited to meet the requirements of our customer.

Concerns with Preliminary Design Concept

Discussion with the sponsor following the Preliminary Design Review (PDR) revealed some potential issues in the preliminary design. The main concern was that the total combined height of the panels decreased significantly between the compressed and relaxed state. The team felt that this was an important issue to be addressed, but that it did not require a total redesign in that it could be fixed with small changes to the shape and dimensions of the plates.

Another result of the PDR was the decision to revisit some of the design concepts that were explored previously. In an attempt to narrow the scope of the project to fit within the requirements of the senior project class, the team had originally ruled out certain design concepts. However, after discussions with the sponsor, the team decided to spend some time after the PDR to continue brainstorming, and consider combining different concepts into the final design. The concern with the preliminary design was that it essentially functioned in either the compressed or relaxed state, and that it lacked any intermediate states between the two. In order to correct this, the team decided to consider some type of medium between the plates that would provide some resistive force to the load, which would create a proportional relationship between the load and the displacement of the plates. Previous research and brainstorming yielded several possible considerations: a gel-like material, high temperature rated polymers, and springs.

Exploration of Other Concepts

The first step in this secondary brainstorming stage was to research the feasibility of these different ideas. The idea for a gel-like material in between the plates was originally inspired by the jelly-like substance found in between the vertebrae in the human spine. The main concern with such a material was that having a gel or liquid in between the plates would make the design unnecessarily complicated. The team foresaw a number of problems, not only in finding a material that was suited for the high temperature application, but also in configuring a system that would allow the gel to either move out of the way of the plates when compressed. Additionally, a gel was limited in that while it would still allow for the plates to compress, it would not provide enough of a displacement to allow for the desired variable load states. Therefore, we decided that pursuing such a material was not feasible for the scope of our project.

Another concept that we researched further was a polymer rated for high temperatures. The main problem that arose with the polymers was that those that could withstand the high temperature constraints were expensive and not very readily available. Additionally, we ran into the issue that most of the polymers we found did not have the necessary spring constant to satisfy our project's requirements. Most of the high temperature polymers were too stiff to allow for the necessary displacement. While the desired displacement of the plates is rather small, it is still important for the plates to be able to move relative to each other without too much resistance, so as to allow for the variable loading states. Another concern was whether or not the polymers could withstand continuous compression without permanently deforming. Through our research on the subject, we realized that while a polymer for our application may exist that it would require too much additional research. Therefore, we decided that in order to be able to complete the project within the allotted timeframe we would not pursue the idea further.

We also considered using a hydraulic system to separate the plates. We started by researching small-scale hydraulic systems such as those commonly used with disc brakes in a bicycle. A basic hydraulic disc brake system has three main components: a small piston, the lines, and the fluid. In a bicycle, the piston is actuated by the rider pulling on the brake lever. Actuating the piston is necessary to create the pressure within the system. Since the goal of our project was to make a system that could function with as little user input as possible, we felt that a system of this type was not ideal for our application. Further, a small hydraulic system would add at least a pound of weight to the system. This was undesirable, since our goal was to design a pack under 3 pounds. Additionally, the hydraulics add a level of complication to the design that would increase the time and cost of manufacture significantly. We were also concerned about how the hydraulics would handle in the high heat application of our project. With hydraulic brakes on bicycles, the heating of the fluid is actually a very common problem. Excess heat in the fluid causes the system to be over pressurized, which can have damaging effects on the piston, and the system as a whole. Additionally, if the fluid gets too hot, it can start to boil, which causes undesirable air bubbles to form in the system. Because of our concerns with whether or not the hydraulic system would function well under the high temperatures we are designing for, we decided that it added too great of a level of complication to pursue further.

Taking a second look at springs, we were immediately drawn to the fact that they are available in so many different sizes, types, and materials. Being able to purchase off-the-shelf springs would be advantageous in that it would allow us to easily switch out and test different springs in later iterations of the design. Further, springs met our requirements to be able to function in compression and also to allow for variable displacement. We looked at a number of different types of springs to determine what would best suit our application. One type of spring we considered was a wave spring. These were interesting in that they are able to withstand the same forces and deflections as standard coil and compression springs, but are approximately half the overall length of a comparable coil or compression spring. With further research, however, we found that the wave springs did not provide the necessary spring constant and overall displacement that was necessary for our application. We also considered leaf springs, but eventually decided that standard compression springs were the most practical for our purpose because of their simplicity and availability in a wide range of sizes and stiffnesses.

CHAPTER 4: FINAL DESIGN

4.1 DESIGN OVERVIEW

The final design is an iteration of the concept presented during the Critical Design Review. It utilizes the same sliding plates idea as before, but incorporates a set of compression springs, steel cables, and steel rods into the system. As discussed previously, the springs provide a force to oppose the weight. This ensures that the plates will stretch out in the case with no load, and will allow the plates to displace relative to the load being carried. The system is designed so that at a load of 45 pounds the plates will touch, and the system will be in the fully compressed state. Figure 17 below illustrates the final design.

Figure 17. Front and back views of the Spring Design.

The design features five curved plates that are allowed to slide up and down along the plane parallel to the user's back. Two steel cables are inserted into the outer two aluminum rods of the plates and hold the plates against the users back. Two steel rods are inserted into the center two aluminum rods of the plates to prevent buckling between the plates when loaded. Because the cables and rods are thin, they are able to bend with the user, but also provide enough structure to keep the plates in place along the user's back. The bottommost plate is the only panel that is actually fixed in the vertical plane. The four remaining panels are able to slide up and down.

Between each panel is a set of four compression springs that push the plates away from each other in the relaxed state and are compressed when the pack is under load. In order to house the springs without having to drastically increase the thickness of the plates, we decided to utilize potted inserts in our composite panels. A potted insert is a rod or tube that is incorporated into the actual composite piece. This allows us to integrate a spring of any size into the plates because we can vary the size of the tube that is inserted without having to change the thickness of the plate. The potted inserts are shown in Figure 18.

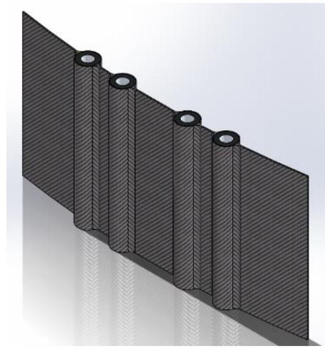

Figure 18. Composite plate with potted inserts.

In order to be able to accommodate springs on both the top and the bottom of the plates, we had to find a way to separate the top and bottom springs. Our solution was to thread about one inch in both ends of the aluminum tubes. With the ends threaded, we can put a set screw at each end to locate the springs as is shown in Figure 19. One benefit of using the set screws is that it allows us to leave the middle portion of the tubes hollow, which drastically reduces our overall weight. Further, because the set screws are able to move, we will be able to test out different length springs without having to reconstruct the entire plate.

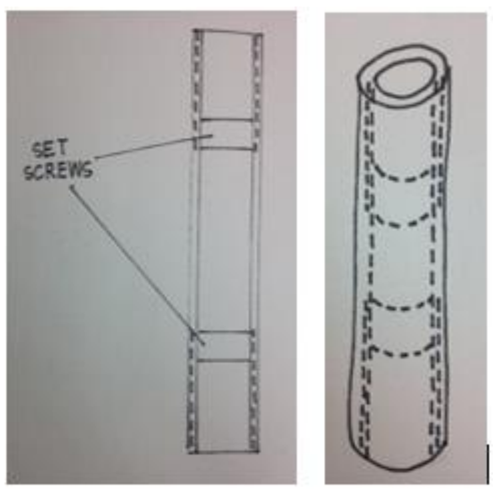

Figure 19. Potted Inserts section view (left) and isometric view (right).

4.2 MATERIAL SELECTION AND PART GEOMETRY

In order to meet our design requirements, we selected carbon fiber for the plates because of its high strength to weight ratio. The alternative would have been to fabricate the plates out of aluminum or steel. However, this would have resulted in parts much too heavy for our application. We chose aluminum 6061-T6 for the potted inserts because it is lightweight, easy to machine, and satisfies our loading cases as is detailed in the following analysis section. In order to utilize as many off-the-shelf components as possible, we determined the size of the potted inserts based on the springs readily available. The selected springs have an outer diameter of 0.247 inches, so we selected a 5/16 -24 thread size with an inner diameter of 0.270 inches. The length of the set screw was determined by analyzing the stresses on the aluminum threads with a factor of safety of 2 and matching that to the standard sizes available. We decided to go with a 0.5 inch length for set screws. The set screws feature a hole with a diameter of 0.125 inches to accommodate the steel rods and cables.

For our prototype, we decided to size the system to fit the average height of all of the team members. Based on an average height of 5' 9", the height of the backpack is 18 inches. Discussions with the sponsor led the team to set the maximum total displacement of the system to 0.75 inches. Therefore, the height was set to 3.45 inches for each of the five plates. The width of the plates was dependent on the outer diameter of the aluminum rods, the bolt head for the waist belt mount, and the clips used to attach a pack. With all of the variables sized, the overall width of the plates was set at 8.75 inches, which is well under the design requirement of 18 inches.

4.3 DESIGN ANALYSIS

An engineering analysis was performed on several components within the overall design. Based on these calculations and assumptions, the validity of the design was confirmed. The following section describes and summarizes the analysis of the plate sizing, spring configuration, and the loading cases. Using methods developed in ME 329, Intermediate Design, and ME 412, Composites, the plate structures were analyzed. It shall be noted that several assumptions were made to simplify the analysis.

Plate Sizing

The overall size of the articulating system was determined based on anthropometric data provided to us by Wolfpack Gear. The total height dimension was specified to be 18 inches nominally. To find the height of a specific plate, both the number of plates and the relaxed distance between the plates needed to be specified. We decided to use five plates in our design. Five plates allowed for a symmetric design of the articulating system and did not create an excess amount of parts. The overall movement of the system from relaxed state to stiff state was designated to be 0.75 inches. With five plates and four gaps between the plates, the distance between each plate was calculated to be 0.1875 inches. The sizing of the plates is dependent on both the number of plates and the total required movement of the system. By changing these two parameters, the size of a specific plate is affected. Given the values stated above, each plate is 3.85 inches tall.

Spring Configuration

The springs were chosen using Hooke's Law. At its simplest level, Hooke's Law describes the force needed to displace a spring a certain distance. A spring factor, K, is used to relate the two quantities. Equation 1, below, shows Hooke's Law, where force is defined as F, and displacement is given by x.

$$F = Kx \qquad \text{(Eqn. 1)}$$

For our application, springs are to be used in parallel. In order to find and size a group of springs that would be suitable, an appropriate spring constant needed to be calculated. To solve for spring constant both a displacement and force needed to be specified for the design. The distance between the plates stated earlier along with a load of 45 lbs. was used along with the following modified Hooke's Law equation. At a load of 45 lbs., the plates in the system should touch each other and the fully compressed system support the full load.

$$K = Fnx \tag{Eqn. 2}$$

In Equation 2, which is derived in Appendix C, *n* represents the number of springs in parallel. By using the previously stated value for load and distance between the plates, the required spring constant can be solved for given an arbitrary number of springs. Spring constants for a range of spring quantities were calculated. Online research was completed and a suitable spring was sourced and is included in the prototype materials list. It was decided to include four springs in the design each with a spring constant of 60 lb/in. To accommodate the excess length of the springs, the potted insert system described in the design section was created.

Loading Case 1

The loading of the system was divided into two cases. The first case, discussed here describes the condition when the load is less than 45 lbs. In this case the load is held by the spring system. In other words the plates are not touching and do not directly hold any of the load. Using design knowledge from previous Mechanical Engineering courses and a simple static analysis it was found that the load is held by the threads between the set screws and the aluminum tubes. Figure 20 below shows a cross section of the load bearing area. The aluminum potted inserts will be threaded 5/16-24 UNF to a depth of 1.5 inches. ½ inch steel set screws were chosen from an online distributor. The threaded area was calculated using Equation 3 shown below. Information for the threads per inch and mean thread area for the specified UNF threads was taken from *Shigley's Mechanical Engineering Design* [1]. Once the total area was calculated, the applied stress, σ, was found by dividing the applied load by the calculated total area, shown below in Equation 4. The applied load was multiplied by two to account for the load being dynamic and then again a factor of safety of two was applied.

$$Area_{total} = (length)(pitch)(area_{thread} \tag{Eqn. 3}$$

$$\sigma_{applied} = \frac{Load_{applied}}{Area_{total}} \tag{Eqn. 4}$$

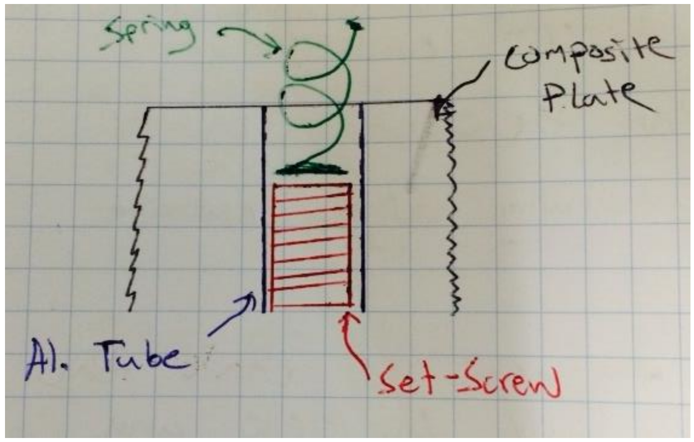

Figure 20. Loading Case 1.

Figure 20 shows the area of the component discussed. The loaded area is depicted in red and labeled set screw. The applied stress was compared to the yield stress of aluminum, due to the fact that it is less than that of steel. The applied stress was three orders of magnitude less than that of the yield stress meaning that the Loading case will not fail. The full calculation of Loading Case 1 can be seen in the hand calculations in Appendix C.

Loading Case 2

The second loading case considered occurs when a load greater than 45 lbs. is applied to the system. Once the threshold of 45 lbs. is crossed, the plates will come into contact with each other. At this point, the composite plates will fully support the entire load. A crude, yet effective method developed in the composites course at Cal Poly (ME 412), was used to analyze the composite laminate on the micromechanics level and size the number of plies needed to support the load. A full derivation of this method is shown in the hand calculations in Appendix C. In this method, it was assumed that the load applied would only be seen by the plates as in-plane shear and axial stresses. In other words, a plane stress state was assumed. This not only made the calculations doable for a composites novice, but also allowed for the use of strength of materials equations rather than a full FEA analysis. Composite material properties for the analysis were taken from a material data sheet that has been used in the ME 412 lecture and lab and is fairly representative of an average unidirectional carbon fiber composite. Although the analysis was rather rough, we followed a standard method that many designers use to get an idea of how a composite design is going to carry the load and whether or not the use of composites is feasible.

The analysis of loading case two was done by breaking the load into its component stresses. These stresses were then analyzed separately. Using the method of line loads, the applied stress was broken up into a shear stress and an axial compressive stress. These two stresses are then turned into line loads. Line loads represent a load acting of a length dimension. The height of the plates dictates the magnitude of the line loads. These calculated line loads are then compared to the allowable line loads for a given ply. For example, the compressive axial stress was turned into a line load in the vertical direction. The goal of a composite design is to carry the load with the fibers of your composite. In this case, the load is vertical so a vertical orientation of the fibers would be appropriate. An allowable line load for a ply of vertical (90 degree) fibers is then calculated from the material characteristics. The applied load is then divided by the allowable load per ply of composite and the number of plies needed in that specific orientation is found. The full analysis of Loading Case two is shown in the hand calculations in Appendix C.

This analysis yielded an important conclusion. The load applied was four times the maximum specified load of 75 lbs. At this load, the applied line loads calculated using the previously explained method were less than 10 % of the line load allowable per ply. In simpler terms, the entire load of the back pack could be held with one ply of this particular composite system. One ply however would not work for this design. At least two plies are needed to hold the potted insert and there is no restriction on having more plies, providing that weight is not an issue with the use of composites. This analysis showed that there is no chance of failure due to the strength of the actual composite being too weak in the direction it is loaded.

In order to create a strong, durable laminate that can not only facilitate the use of the potted insert, but also support both the axial and shear loads, a six ply lamina has been designed. This six ply lamina is symmetrical and includes a set of plus/minus 45 degree plies on the outside surface followed by two 90 degree plies in the center. The plus/minus 45 degree plies, which could be substituted with +/- cloth, will handle the shear stress, along with provide a strong and aesthetically pleasing outer surface for the plates. The 90 degree center plies will carry most of the compressive axial load long with secure the potted inserts. Figure 21 shows a representable sketch of the laminate with the potted inserts.

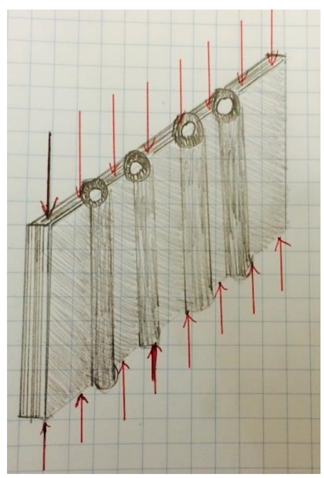

Figure 21. Depiction of laminate analyzed in Loading Case 2.

4.4 COST ANALYSIS

Included in Table 7 is a breakdown of the estimated cost of a prototype. The cost of the prototype is very low because most of the material and components will be provided by Wolfpack Gear. Table 7 also includes a breakdown of cost if all of the materials used in the prototype production needed to be purchased. This mainly includes the materials used in the fabrication of the mold and the composite plates. The components to be purchased for our prototype are off-the-shelf items from Grainger. We chose to source the set screws, springs, the aluminum rod, and steel rods from Grainger because they are readily available and will ship in a minimal amount of time. Additionally, by ordering off-the-shelf components, we reduce the overall cost, machining needed, and assembly time. To further save on cost, all of the composite layups, manufacturing, and machining will be done by the team at the facilities available at Cal Poly, Wolfpack Gear, and the Maker Space in San Luis Obispo.

Table 5. Cost breakdown of prototype.

Item	Amount Needed	Units	Vendor	$/unit	Total Price (prototype)	$	Set	Unit	Total Price*
1/16" Steel Cable	6	ft	Grainger	$0.91/ft	$5.46	0.91	6.00	ft	$5.46
1/2" Unpolished Aluminum Rod	8	ft	Grainger	$.96/foot	$30.70	0.96	8.00	ft	$7.68
1050 denure ballistic nylon	1	yd^2	Wolfpack Gear	N/A	-	0.00	0.00	yd^2	$0.00
3/8"-16 bolt for waist belt	1	-	Wolfpack Gear	N/A	-	0.00	0.00	-	$0.00
5/16"-24 Nonmarring Flat Point Set Screws (1/2")	32	-	Grainger	$.20/screw	$14.46	0.20	32.00	-	$6.40
6K twill dry carbon fiber cloth	10	ft^2	Fiberglast	$63.95/12.5ft^2	-	63.95	12.50	ft^2	$51.16
7/64" Steel Rods	6	ft	Grainger	$0.81/ft	$4.86	0.81	6.00	ft	$4.86
Breather/bleeder cloth	3	yd^2	Fiberglast	$7.95/yd^2	-	7.95	3.00	yd^2	$23.85
Compression Spring 13/16X0.42	16	-	Grainger	$1.26/spring	$20.16	1.26	16.00	-	$20.16
Duratek mold hardener	1	gal	Fiberglast	$95.00/gal	$47.50	95.00	0.50	gal	$47.50
Hi-density foam	1	ft^3	Cal Poly	$0.00	-	0.00	0.00	ft^3	$0.00
Misc supplies (gloves, towels, sand paper, etc)	-	-	-	N/A	$20.00	-	-	-	$20.00
Paint gun	1	-	Wolfpack Gear	N/A	-	0.00	0.00	-	$0.00
Part-all mold release paste	-	-	Fiberglast	$19.95/lb	-	19.95	1.00	lb	$19.95
Plastic peel ply	3	yd^2	Fiberglast	$4.95/yd^2	-	4.95	3.00	yd^2	$14.85
Resin/hardener	-	-	Fiberglast	$49.95/lb	-	49.95	1.00	lb	$49.95
Sealing Tape	-	-	Fiberglast	$7.95/roll	-	7.95	1.00	roll	$7.95
Vacuum pump	1	-	Wolfpack Gear	$400.00	-	0.00	0.00	-	$0.00
Vacuum tubing	-	-	Fiberglast	$1.45/ft	-	0.00	0.00	ft	$0.00
				Total	$143.14			Total	$279.77

* If all materials needed to be purchased

CHAPTER 5: PRODUCT REALIZATION

5.1 MANUFACTURING PROCESSES EMPLOYED

The manufacturing of the prototype consisted mainly of producing the composite plates that make up the articulating spine system. This comprised of creating a mold and using that mold in a layup process to create the final carbon fiber parts. With help from our sponsor and the use of the lab and shop space on campus, our team was able to do all of the manufacturing in house. The project sponsor provided all necessary composite materials. The foam for the mold was supplied for by the Hangar machine shop and supplies for creating the mold were purchased from the SAE Baja team. Rather than buying mold making supplies, it was much less expensive to share with the Baja team, who already had an excess of the materials that were required.

The mold was manufactured first. A negative part model was created on Solidworks. This negative part model was entered into the Shopbot in the Hangar and mold was milled out of high-density foam. Figure 22 shows the Shopbot milling the mold used to manufacture the composite plates.

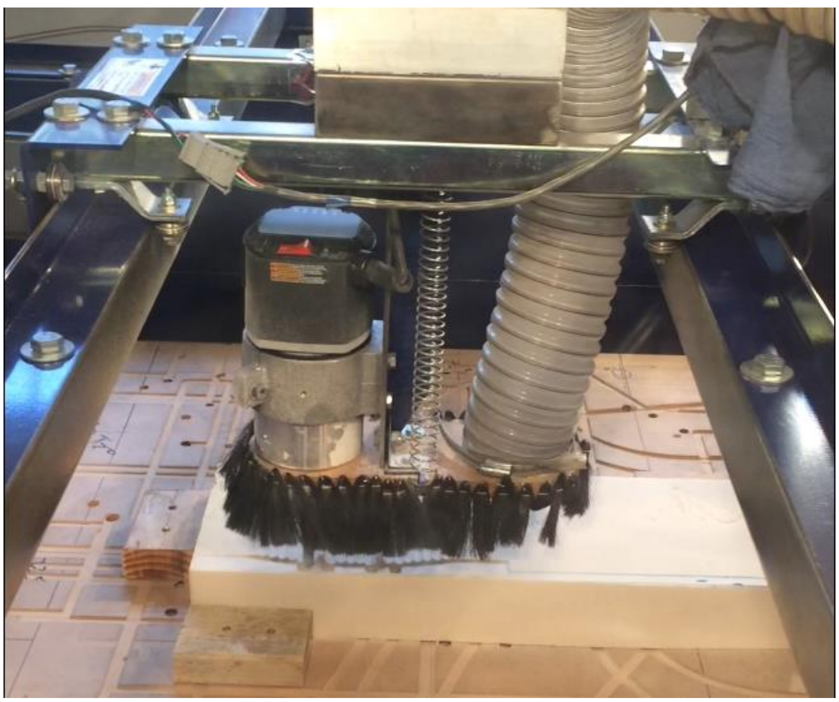

Figure 22. CNC router milling design from foam.

Once the mold was milled, a mold sealer was sprayed on the mold to seal the surface. After the mold sealer had cured, the Duratec process was started. Duratec is a mold-hardener that is used to create an appropriate surface for molding composite parts. Four layers of Duratec were used to ensure a proper surface finish on the carbon-fiber part. Between each layer of Duratec, the mold was sanded to remove any inconsistencies or imperfections. Figure 23 below shows a sanding phase of the mold preparation

Figure 23. Sanding the mold between layers of Duratec.

With the mold created, the lay-up process could begin. . There are several different methods used for creating composite parts that range from resin transfer systems, where the resin is sucked through the fiber material as it lays in the mold, to composite particle injection molding. For this application, it was decided to use a wet lay-up process. In the wet lay-up process, the carbon fiber cloth plies are saturated with the epoxy resin individually and laid onto the mold one at a time. This was advantageous for this project, as it was required to insert the potted insert in between the middle two plies. Once the plies are saturated and laid into the mold, a vacuum bagging processes is used to place the part under a vacuum. This vacuum is held on the part for ten to twelve hours. Figure 24 below diagrams the wet lay-up process along with the vacuum bagging process.

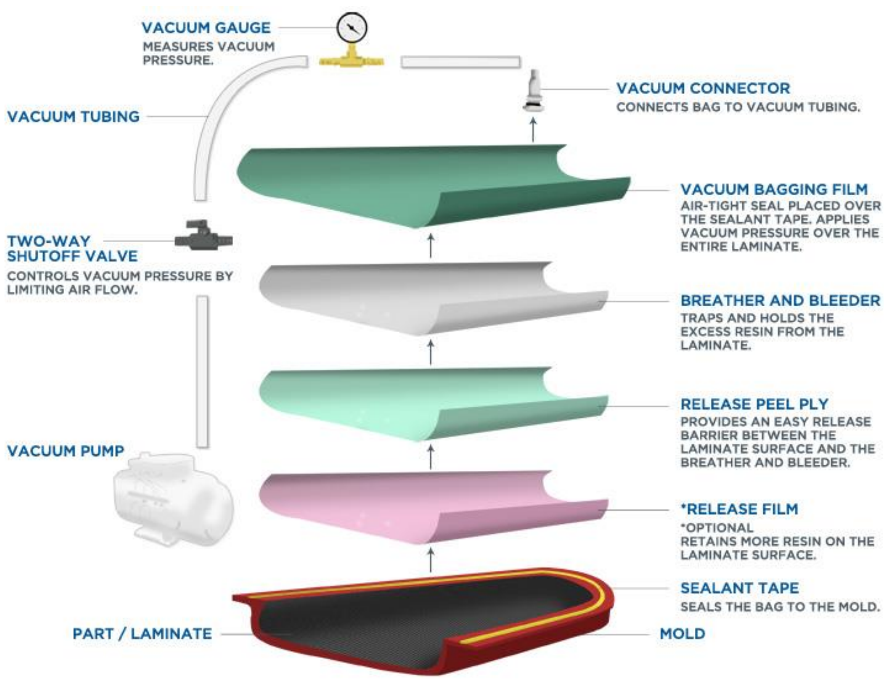

Figure 24. Diagram of vacuum bagging and wet lay-up process.

The first attempt at creating a carbon-fiber plate from the mold ended negatively, as seen in Figure 25 below. A combination of weak foam, excess resin, and poor release agent caused a part of the mold to stick to the composite part as it was pulled off the mold.

Figure 25. First attempt at pulling composite part off of mold.

This mold was deemed unrepairable and the team had to produce a new mold. Figure 26 below show the new mold along with the vacuum bagging process used. This mold was used to fabricate the remaining four plates.

Figure 26. Vacuum bagging process for laminate curing.

A part pulled out of the mold, as seen in Figure 27, had to be machined down to the appropriate size. The potted inserts were cut to length and completely bored out before being laid up in the composite. Once the part was cut to size, the aluminum inserts were given a finishing pass with the tap. Once all five of the plates were completed, the system was ready to be assembled.

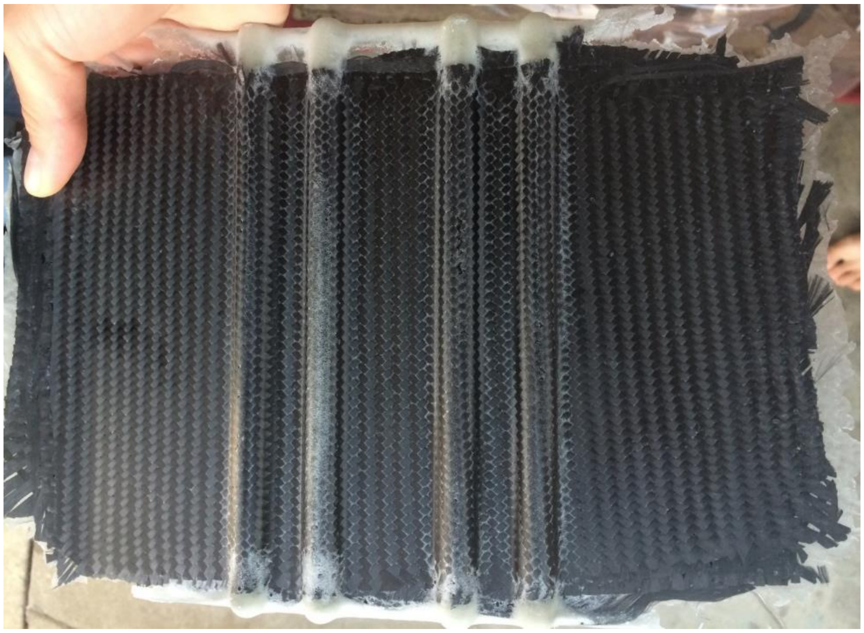

Figure 27. Example composite after molding/curing process.

The shoulder straps and waist belt were supplied by the sponsor along with all the webbing and buckles used on the prototype. The steel cables and steel rod were purchased separately. The prototype was assembled, tested, and iterated upon. The final prototype was the product of different iterations that took place during the final assembly phase.

Design Changes:

The overall design concept remained similar to the idea proposed during the concept design review. However, there were a few modifications to the system that materialized during the manufacturing process. The most significant change was in the switch from the fabric panel with sleeves to the minimalistic cable approach. Observations of the way the wooden plates moved within the fabric sleeves raised concerns about how the system would prevent the plates from buckling when heavily loaded. In order to remedy this, cables were run through the five plates in an attempt to prevent the system from bowing out. Once this idea was established, the team decided to do away with the fabric panel and sleeves altogether since it was now redundant. Eliminating the fabric components also significantly streamlined the spine design, which added to the aesthetic appeal and overall functionality.

Loading of the spine system during testing showed that the cables alone were not enough to prevent the plates from buckling. The cables running through the two center aluminum inserts were replaced with thin wires. The team tested out several different materials and thicknesses before deciding on a 7/64" steel wire. It was chosen because it allowed enough flexibility within the system while providing adequate rigidity to the spine to prevent buckling.

Another iteration to the design was the spacer added to the pivot point on the waist belt. Initial testing showed that in addition to buckling, the plates formed slight angles with each other as the system naturally bent towards the curvature of person's back when the pack was loaded. Adding the spacer on the waist belt created a vertical line from the waist belt to the shoulders, which, in combination with the steel wires, kept the plates oriented correctly. Further, the spacer held the moving plates just slightly off of the back, which increased the overall comfort of the system since it reduced the points of contact with the body.

While our quantitative testing proved largely inconclusive in itself, the testing process as whole was crucial in perfecting the final design. It was the iterative process of testing and modification that resulted in the functional final prototype.

Manufacturing Recommendations:

In order for the prototype design to be put into production, there are a few changes that would be made to reduce the overall manufacturing process. The first change would be to order aluminum tubes with the desired inner diameter. Because the aluminum tubing was significantly more expensive than a solid rod, the team opted to purchase solid aluminum rods and bore the through holes on the lathe at the machine shop.

Another change would be to streamline the carbon fiber wet layup process. Because the team only had access to a small vacuum pump, it was only possible to do one layup at a time. However, with multiple vacuum pumps, or a larger vacuum pump, it would have been possible to lay up all five plates in one day. With the current method, the entire layup process took about 24 hours per plate. This was due to the fact that the mold surface had to be prepped between each of the layups which took a few hours. Additionally, the carbon fiber required a significant amount of time to cure. Therefore, had all plates been curing simultaneously, the time could have been reduced considerably.

The last recommendation to improve the manufacturing process would be to develop a better method of cutting the plates. Because the plates for the prototype had a slight curvature to them, it was not possible to use the vertical band saw to trim the plates without bending them. Therefore, the only way to trim the excess was to saw by hand, which took a significant amount of time. One solution to this would be to create a jig upon which the curved plates could rest, so that there was no concern of bending when force was applied. This would allow us to utilize the vertical band saw or a similar machine instead of cutting by hand. Which, once again, would decrease the overall manufacture time.

CHAPTER 6: DESIGN VERIFICATION AND TESTING

Design verification of the prototype was completed mainly on a qualitative basis rather than a quantitative basis. The backpack industry along with Wolfpack Gear in particular judge the validity of new designs by means of user response and qualitative metrics. How a product "feels" and if moving with the product on "feels" natural, are examples of tests used to validate a product. Methods found in other more technical design approaches were attempted but results were relatively inconclusive. These tests are described below along with the qualitative tests that were carried out.

Originally, testing to obtain the material properties of the composite plates was planned. Throughout the manufacturing and assembly process it was deemed that these quantities were not necessary for the evaluation of the prototype and time would be better spent testing and modifying the overall design of the system. The original Design Verification Plan and Report (DVP&R) designed by the team was unrealistic for the assembled prototype. Inexperience with the product-user interface encompassed by backpack design and ambitious initial testing ideas led to an unattainable testing scope for the project. Through discussions with the project sponsor advisor, the testing completed has been deemed acceptable. Future development of the prototype and concept could utilize the testing protocols originally designed for this project.

6.1 Quantitative Testing:

Quantitative testing was carried out in the attempt to numerically quantify the amount of weight being distributed through the articulating spine, away from the shoulders, to the waist belt. Two different methods were attempted. The first method used a digital spring scale to measure the tension in the shoulder straps. The spring scale, shown in Figure 28, was hooked up between the bottom of the shoulder strap and its attachment point on the waist belt. With the assumption that the tension in the shoulder strap would be equal throughout the strap, the system was loaded and a reading on the scale was taken. The weight in the pack was varied in an effort to measure the change in tension felt in the shoulder straps as the weight of the load was varied. The pack weight was varied from no load to 40 pounds. The measurements taken from the digital spring scale did not follow any particular trend and did not provide viable data that could represent how much of the load the spine system was transferring away from the shoulder straps and to the waist belt.

Figure 28. Digital spring scale tension test.

With the previously discussed test yielding inconclusive data, a separate test was devised and carried out. By measuring the change in distance between the plates as the system is loaded, and then using basic spring equations, the force in the springs between the plates could be calculated. The force in the springs is, in theory, equal to the load that the spine system is transmitting to the waist belt. The difference between this spring force, and the load in the pack would be the load that the user is feeling in the shoulder straps. Figure 29 below shows space between the plates being measured as the spine system is loaded.

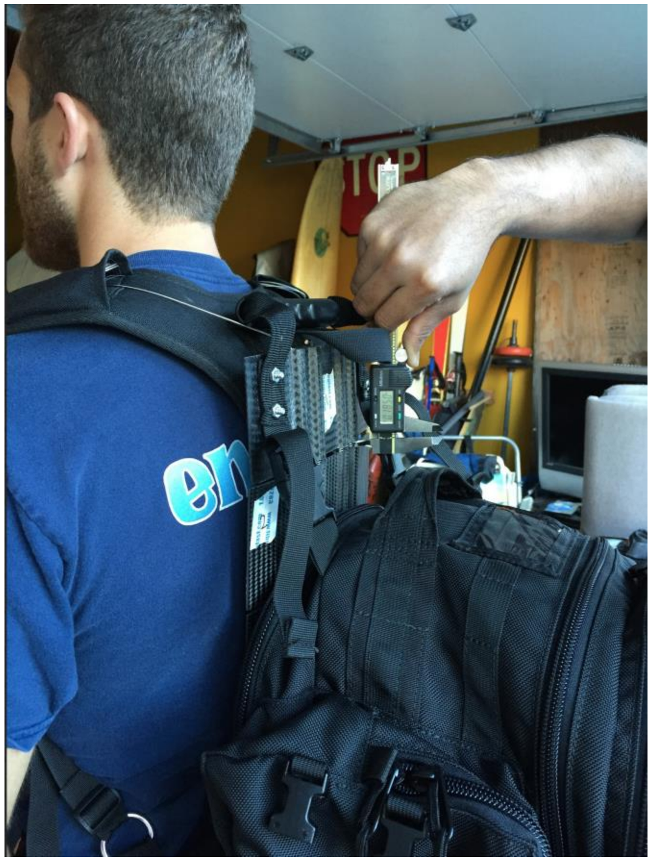

Figure 29. Measuring distance between plates to determine force in springs.

These measurements and calculations were taken for a range of loads. Again the calculations yielded results that were inconclusive. Based on the brief calculations, the spring force was greater than the load in the pack, which is physically impossible. It was decided that there were other interactions that were affecting the load distribution in the spine system.

The quantitative testing and lack of conclusive results demonstrated that the models we used to devise these tests were incorrectly simplified. Small angles created at the joints between the plates, along with other contact points between the user and the spine system affect the load distribution and greatly complicate the path that the load takes once it is applied to the system. Human factors also played a role in the quantitative testing problems. There was no life-sized figure to wear the pack for testing other than one of the group members. While testing, the wearer of the system attempted to remain relatively motionless. However, small involuntary motions, such as leaning slightly forward or backwards, breathing, tensing of the neck and shoulders, and small movements of the arms affected measurements. With more time and more resources, quantitative testing on a more precise and more successful scale could be achieved.

6.2 Qualitative Testing:

Qualitative testing proved to be the most conclusive way to validate the performance of the prototype. By trying on the system, loading the system, and moving around while wearing the system, the team was able to discuss the successfulness of the prototype. A comparison between the prototype and the current shoulder-strap system, shown below in Figure 30 was also used. By loading the spine system and the currently used strap system with the same load, the difference in load felt in the shoulder strap could be felt. With light weight, the load felt in the shoulder straps was almost non-existent. As the weight in the pack was increased, the load felt in the shoulders increased slightly but was far less than the load felt in the shoulder straps of the currently used strap system.

Figure 30. Web-gear harness currently produced and sold by Wolfpack Gear used for comparison during qualitative testing.

Through the qualitative testing process, loads ranging from ten pounds to fifty pounds were applied to the spine system. The system did not fail and successfully transmitted most of the load to the waist belt. When compared to the Web-gear harness, the load felt in the shoulder straps was significantly reduced. Movements undertaken while wearing the system were not hindered by the spine system.

As is common practice in the back-pack industry, the qualitative tests administered validate the success of the prototype. The prototype did not fail under a max loading case of fifty pounds and exceled when compared to the currently used product.

CHAPTER 7: CONCLUSION AND RECOMENDATIONS

Overall, our team was satisfied with the completion of the project. We accomplished our goals of designing and building a low-profile articulating backpack spine that functioned in both a rigid and flexible state. As is true with the end of any project, there are always things that we would improve if given more time. However, with the timeline allotted, we feel that we accomplished our goals of carrying a project from start to finish from the initial brainstorming to a working prototype.

The main area that we would have liked to delve deeper into would be to develop a more thorough testing apparatus. As discussed previously in the report, testing was one of the most difficult areas of the project for us. Because every person is so different not only in body shape and stature, but also in the way that they stand and walk, it was difficult to gather any sort of controlled test data. Also, in trying to complete the testing, we realized that theoretically modeling the forces at play in a backpack is much more complicated than it seems initially. This is because the forces are constantly changing with the most miniscule differences in the way a person moves. Even something as small as the test subject taking a deep breath, is enough to alter the orientation of the plates, and thus changes the way that the forces are applied. Therefore, had we more time and increased resources, we would have developed a more standardized testing apparatus to allow us to determine quantitatively how well the backpack performed.

Another area that we would improve if the project were to continue would be to modify the design to increase the manufacturability and marketability. Since the goal of our project was to prove the concept of our design, we purposefully designed room for adjustment within our spine. This allowed us to adjust small factors within the system without redesigning and rebuilding in entirety. The main example of this was the set screws used to locate the springs. We chose to use the set screws because of the versatility that it allowed us in modifying the distance between the plates. However, if the design were to be manufactured on a larger scale, the set screws would likely be replaced by a more permanent fixture within the rods that would not require so many small parts to be assembled.

Further considerations for design improvement would be to cut down the overall weight and size of the system. In order to stay within the timeline of the project, the group decided to use springs as the compressive element between the plates because of their widespread availability and ease of ordering. However, provided more time and funding, it would be possible to find something such as a compressive polymer or hydraulic system that could replace the springs and be more lightweight. Another way to cut down on the total weight would be to modify the potted inserts. During the design process the team considered replacing the aluminum rods with PVC pipe to decrease the weight of the system. However, because of the team's unfamiliarity with PVC in regards to the unique conditions it would be under, it would have been necessary to perform a significant amount of research and analysis that the short timeline of the project just did not have room for. The easiest way to cut down on weight and increase overall mobility would be to alter the size and shape of the plates. Because the plate size and shape was dictated by the orientation of the springs and the inserts, were those components to be altered, the overall system could be much more streamline.

Overall, we felt that the project was a success in that we took an idea provided by our sponsor and presented them with a unique and plausible solution. While the prototype design would require some modification in order to be a practical and marketable product, we believe that the design proves the validity of the concept and thus could warrant further consideration.

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ATTACHMENTS:

Appendix A:

1. Problem Statement and Requirements as Provided by Wolfpack Gear
2. Quality Function Deployment (QFD) Diagram
3. Pugh Matrices
4. Decision Matrix

Appendix B: Detailed Part Drawings, Assemblies, and Bill of Materials

Appendix C: Detailed Supporting analysis

Appendix D: Gantt Chart and Smart Sheet

Appendix A:

Problem Statement and Requirements as Provided by Wolfpack Gear

CARBON ARTICULATING BACKPACK SPINE

PROBLEM STATEMENT

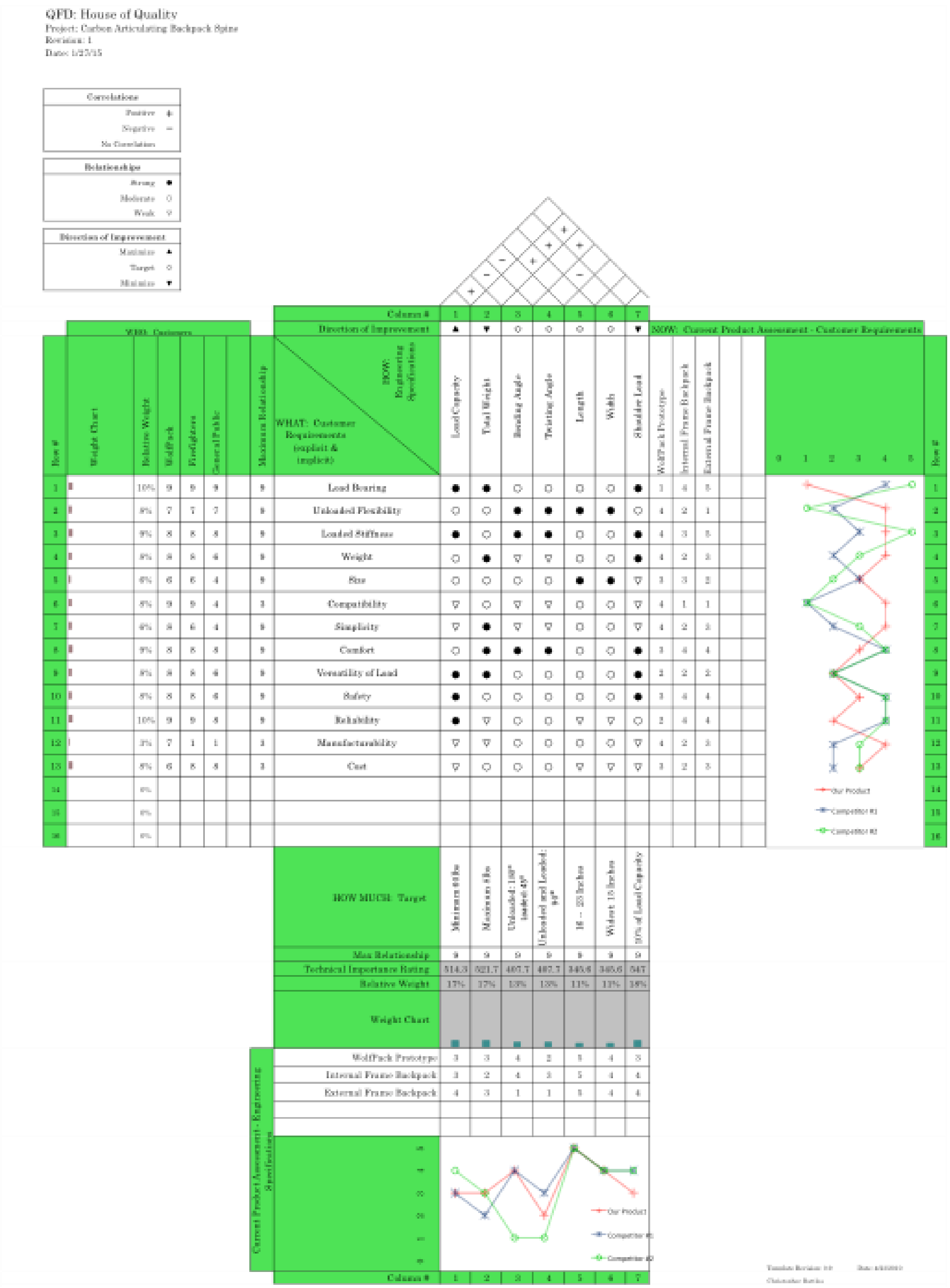
While fighting a wildfire, a firefighter is expected to execute a wide range of tasks. These tasks might include digging trenches, carrying hoses, felling trees, etc. Space is limited for a firefighter so for the duration of a normal two to three week job each worker carries the same pack all day every day. For this reason backpacks designed for firefighters must accommodate the firefighter who might be carrying fifty pounds of hose one day and the following day carry nothing more than a shovel, food, and water. Similarly, backpack comfort and reliability rank paramount in a situation where a firefighter depends on their gear in maintaining both safety and comfort while battling a blaze.

Currently on the market, we typically see internal frame systems for backpacks intended for heavy loads, frameless systems in backpacks intended for light load, but what about in between - a pack intended for heavy *AND* light loads in the same trip? Given that forest firefighters fall into this 'in between' stage, needing a do-all backpack for any situation, a backpack frame system is needed which stiffens under heavy load and articulates when load-free in order to be both load-bearing and conforming. With a system such as this, a firefighter could maintain better comfort, safety, and thus more easily execute their tasks without worry or unnecessary fatigue.

LIST OF REQUIREMENTS

- Build an articulating backpack 'spine' which stiffens when weighted and bends freely when unweighted – much like the articulating action of a crawfish tail.
- The pieces of the system should be made from carbon fiber in order to be both lightweight and strong.
- A load should clip to the frame with male/female plastic buckles.
- The frame should incorporate Wolfpack Gear, Inc.'s current belt system.
- System should be as low profile and space efficient as possible.
- If possible, incorporate the spine system into a firefighter jacket.

Quality Function Deployment Diagram



Pugh Matrices

Table 6. Pugh Matrix with internal frame backpack as datum.

	Design Concepts										
	A	B	C	D	E	F	G	H	I	J	K
1a	+	N/A	S	N/A	S	S	+	N/A	+	+	DATUM
1b	+	N/A	S	N/A	+	+	+	N/A	+	+	
2a	+	N/A	+	N/A	S	+	+	N/A	+	+	
2b	+	N/A	+	N/A	+	+	+	N/A	+	+	
3a	+	N/A	+	N/A	+	+	+	N/A	+	+	
3b	+	N/A	+	N/A	+	+	+	N/A	+	+	
4	S	N/A	S	N/A	S	S	S	N/A	S	S	
5	-	N/A	S	N/A	-	S	S	N/A	S	S	
6	-	N/A	+	N/A	S	-	S	N/A	S	-	
7	-	N/A	+	N/A	S	S	S	N/A	S	S	
8	S	N/A	S	N/A	S	S	S	N/A	S	S	
9	+	N/A	+	N/A	+	+	+	N/A	+	+	
Sum +	**7**	**N/A**	**7**	**N/A**	**5**	**6**	**7**	**N/A**	**7**	**7**	
Sum -	**3**	**N/A**	**0**	**N/A**	**1**	**1**	**0**	**N/A**	**0**	**1**	
Sum S	**2**	**N/A**	**5**	**N/A**	**6**	**5**	**5**	**N/A**	**5**	**4**	

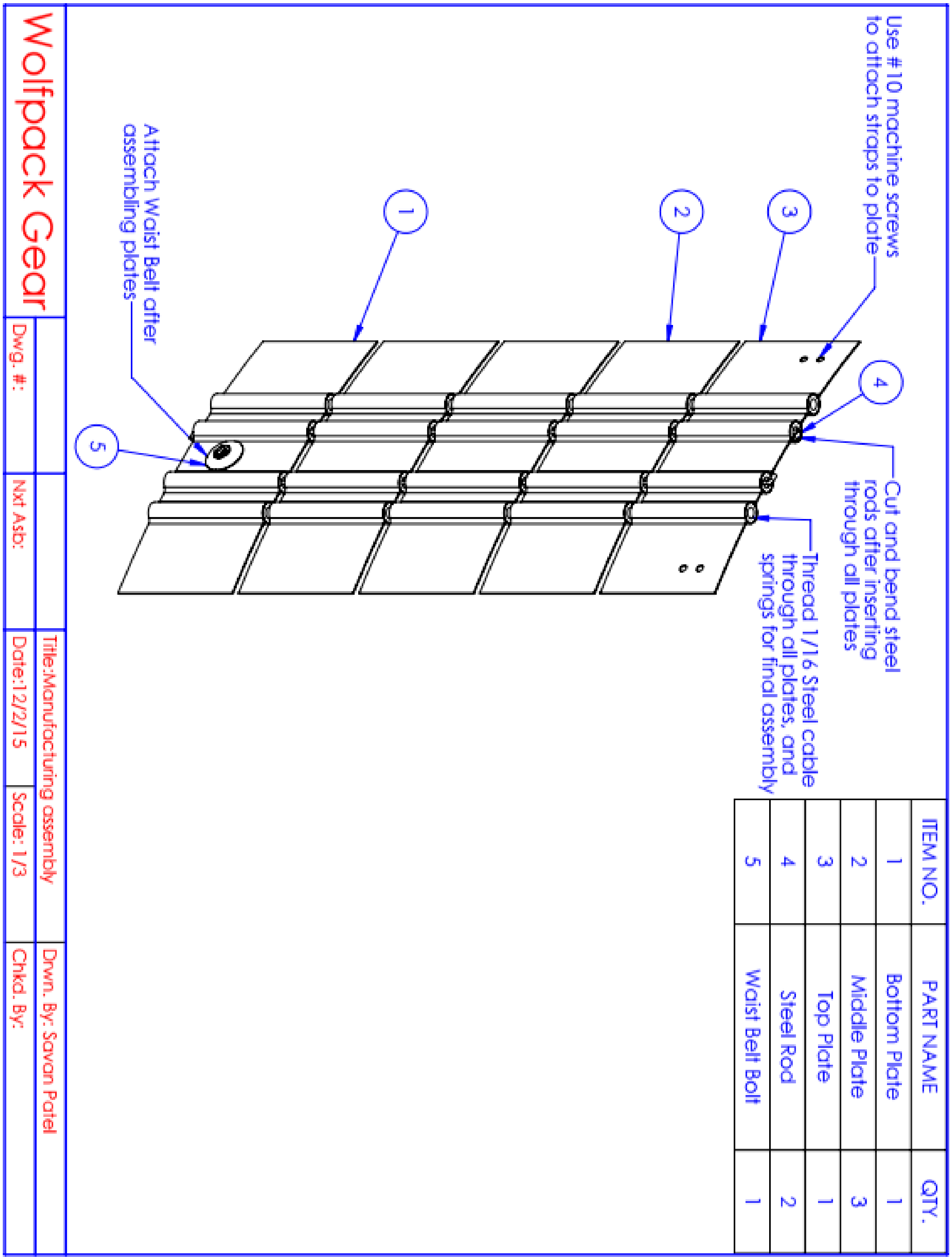
Table 7. Pugh Matrix with rounded sliding vertebrae as datum.

	Design Concepts									
	A	B	C	D	E	F	G	H	I	J
1a	+	N/A	DATUM	N/A	+	+	+	N/A	+	+
1b	+	N/A		N/A	+	+	+	N/A	+	+
2a	S	N/A		N/A	S	S	S	N/A	S	S
2b	S	N/A		N/A	S	S	S	N/A	S	S
3a	S	N/A		N/A	S	S	S	N/A	S	S
3b	S	N/A		N/A	S	S	S	N/A	S	S
4	S	N/A		N/A	S	S	S	N/A	S	S
5	-	N/A		N/A	-	-	-	N/A	-	+
6	-	N/A		N/A	-	-	-	N/A	-	-
7	-	N/A		N/A	S	S	S	N/A	S	-
8	S	N/A		N/A	S	S	S	N/A	S	S
9	S	N/A		N/A	S	S	S	N/A	S	S
Sum +	**2**	**N/A**		**N/A**	**2**	**2**	**2**	**N/A**	**2**	**3**
Sum -	**3**	**N/A**		**N/A**	**2**	**2**	**2**	**N/A**	**2**	**2**
Sum S	**7**	**N/A**		**N/A**	**8**	**8**	**8**	**N/A**	**8**	**7**

Decision Matrix

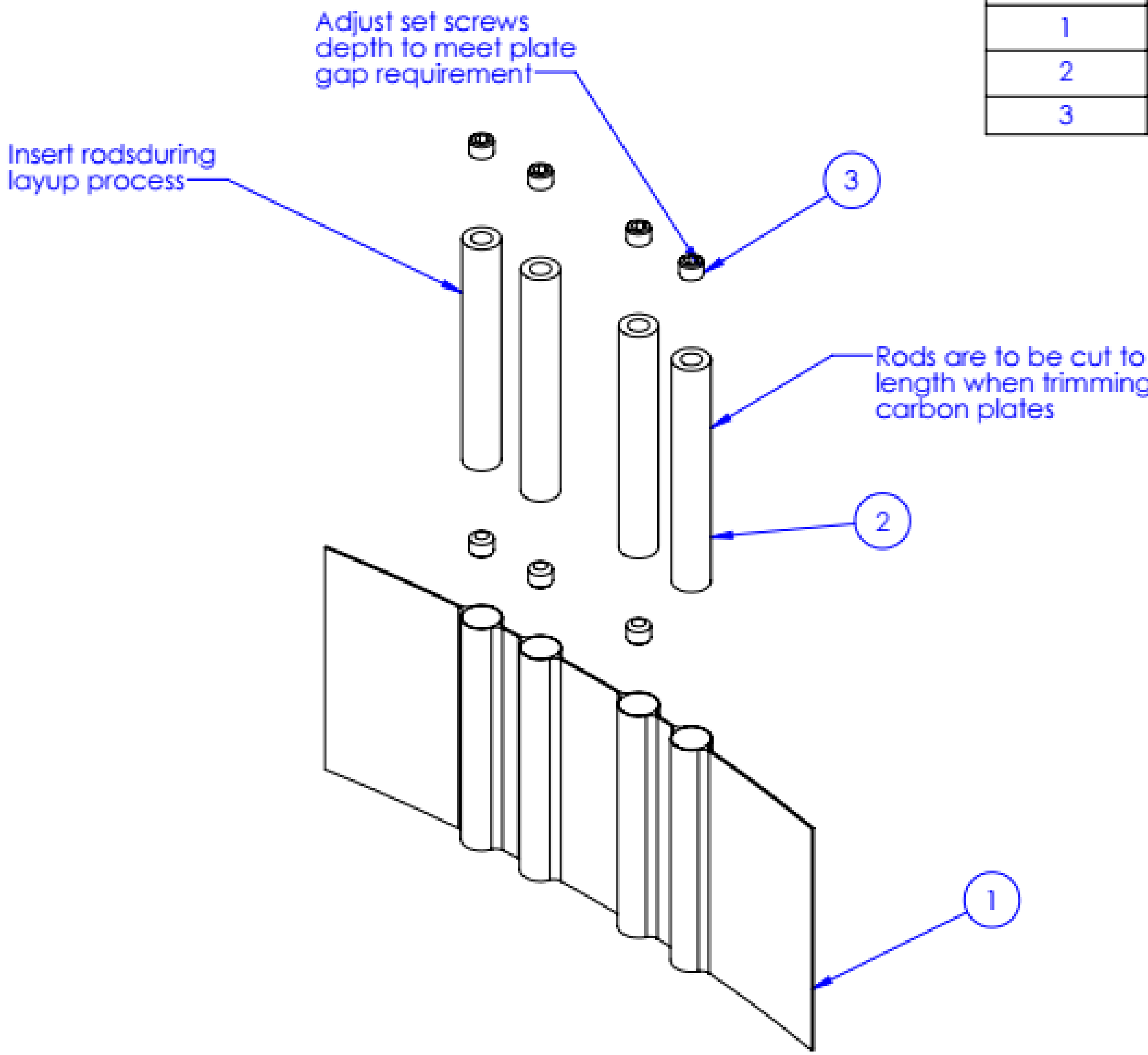
Options	Design Criteria Weight Factor	1a	1b	2a	2b	3a	3b	4	5	6	7	8	9	Overall Score
		0.085	0.065	0.025	0.025	0.05	0.09	0.18	0.18	0.07	0.07	0.08	0.08	
A	Flat Ball/socket	7.65	5.85	1.375	1.625	1	7.65	13.5	12.6	3.5	4.2	6.8	6	71.75
		90	90	55	65	20	85	75	70	50	60	85	75	
C	Rounded Sliders	2.55	2.925	1.875	2	2.5	6.75	13.5	14.4	4.55	4.9	6	6	67.95
		30	45	75	80	50	75	75	80	65	70	75	75	
E	Springs/Sliders	5.95	5.525	0.75	1.875	2.75	7.65	14.4	10.8	3.15	4.55	6.8	6.4	70.6
		70	85	30	75	55	85	80	60	45	65	85	80	
F	Imitation Spine	6.375	5.2	1.5	1.625	3.25	6.3	14.4	10.8	3.85	4.2	6.8	6	70.3
		75	80	60	65	65	70	80	60	55	60	85	75	
G	Bamboo Mat	5.525	4.55	1.625	1.75	3.75	7.2	13.5	13.5	4.2	5.25	6	6	72.85
		65	70	65	70	75	80	75	75	60	75	75	75	
I	Blinds	5.525	4.55	1.625	1.75	3.75	7.2	13.5	12.6	4.2	5.25	6	6	71.95
		65	70	65	70	75	80	75	70	60	75	75	75	
J	3 Panel Pivot	5.1	4.55	1.875	2	3	5.85	14.4	12.6	3.85	5.6	6.8	6.8	72.425
		60	70	75	80	60	65	80	70	55	80	85	85	

Appendix B: Part Drawings, Assemblies, and Bill of Materials



ITEM NO.	PART NAME	QTY.
1	Bottom Plate	1
2	Middle Plate	3
3	Top Plate	1
4	Steel Rod	2
5	Waist Belt Bolt	1

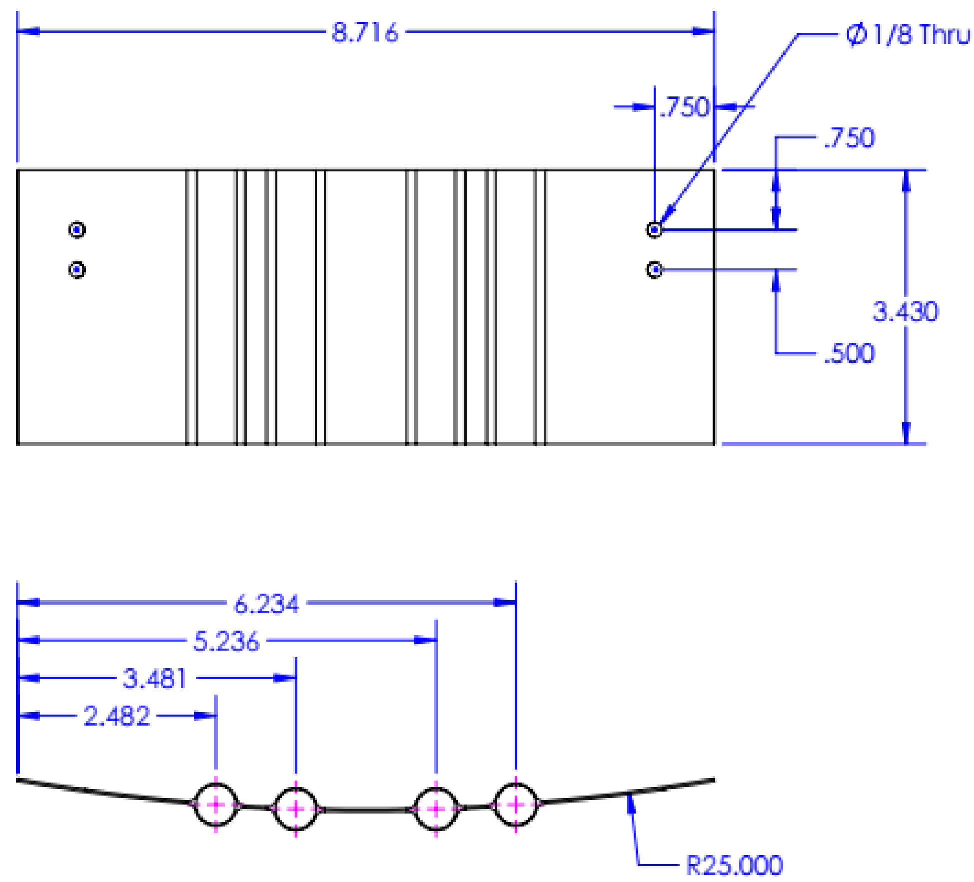
ITEM NO.	PART NAME	QTY.
1	Carbon Plate	1
2	Tapped Tube	4
3	socket set screw	8



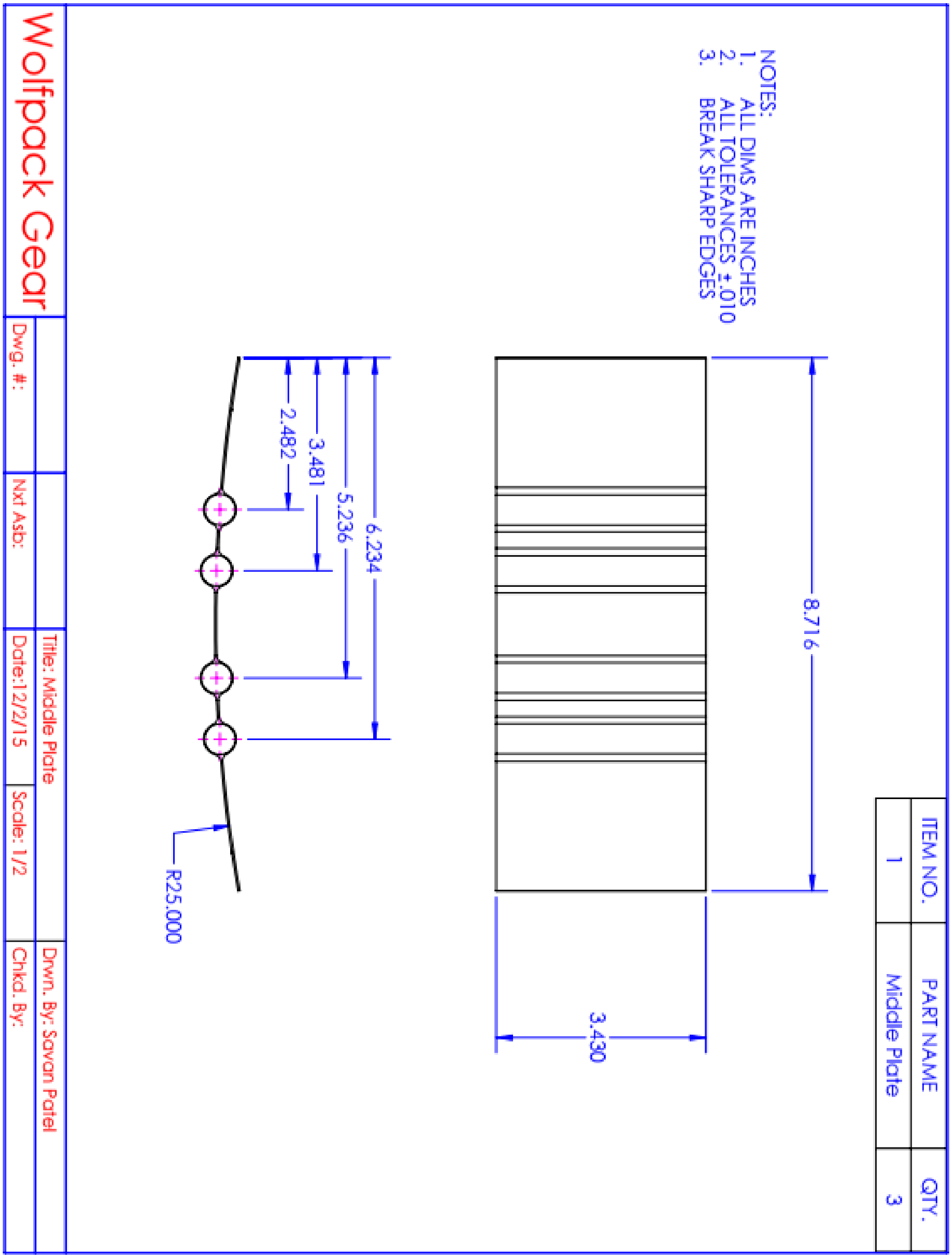
Wolfpack Gear			Title:Plate assembly		Drwn. By: Savan Patel
	Dwg. #:	Nxt Asb:	Date:12/2/15	Scale: 1/2	Chkd. By:

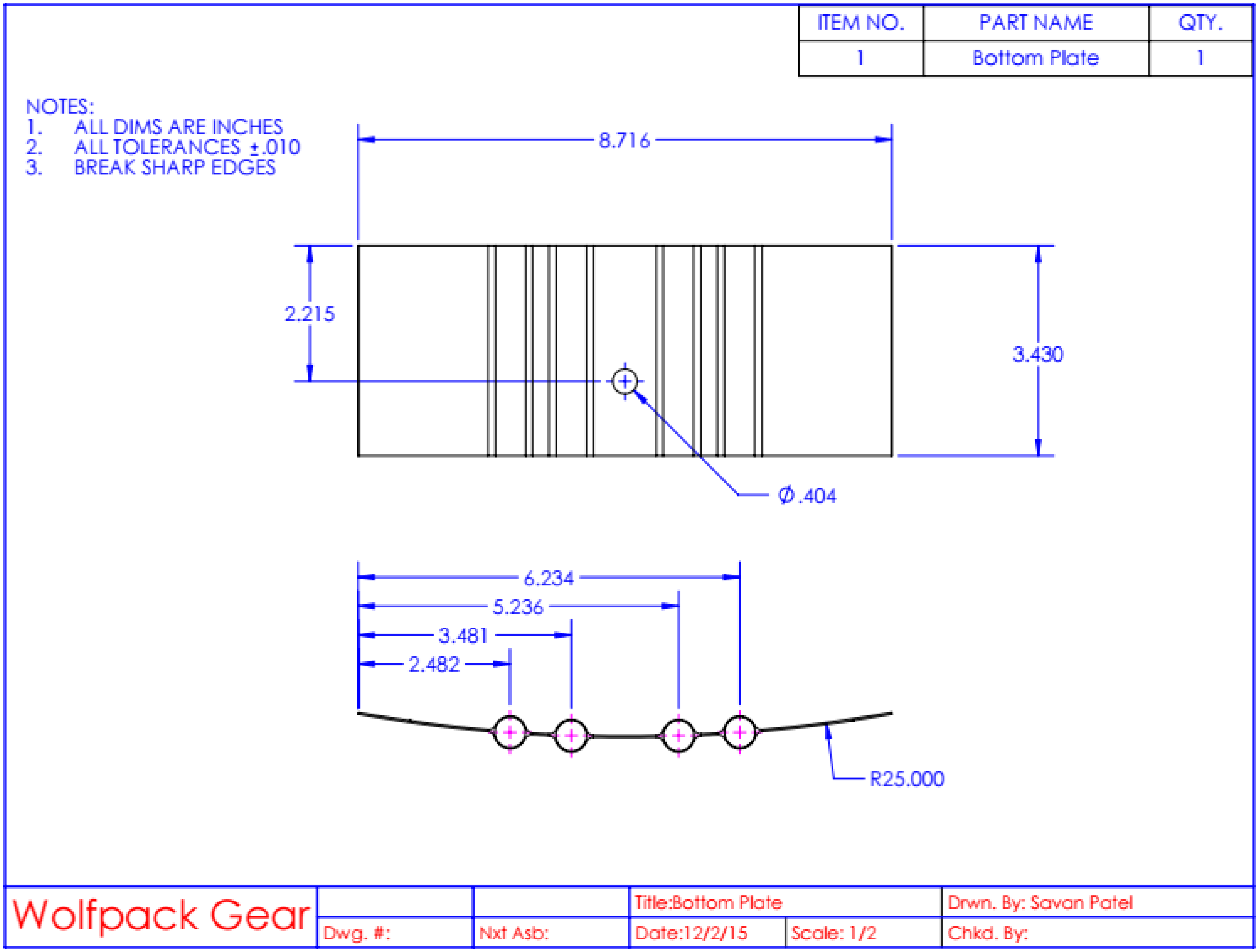
ITEM NO.	PART NAME	QTY.
1	Top Plate	1

NOTES:
1. ALL DIMS ARE INCHES
2. ALL TOLERANCES ±.010
3. BREAK SHARP EDGES



Wolfpack Gear			Title:Top Plate		Drwn. By: Savan Patel
	Dwg. #:	Nxt Asb:	Date:12/2/15	Scale: 1/2	Chkd. By:

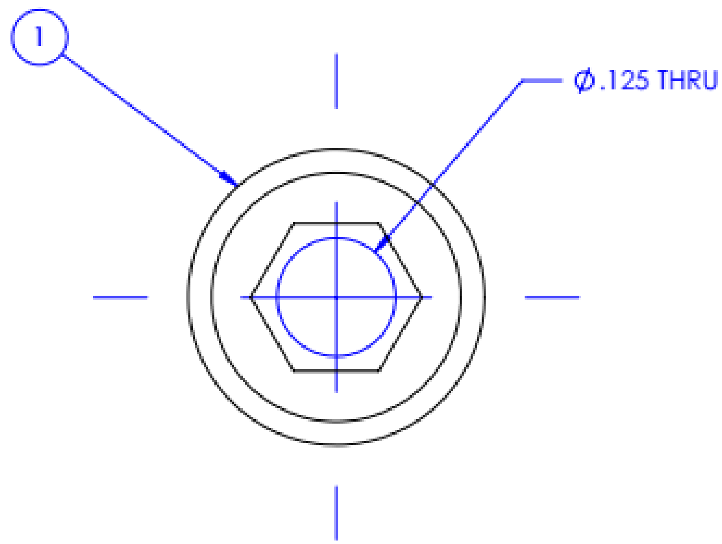

NOTES:
1. ALL DIMS ARE INCHES
2. ALL TOLERANCES ±.010
3. BREAK SHARP EDGES
ITEM NO.
PART NAME
QTY.
1
Middle Plate
3
8.716
3.430
2.482
3.481
5.236
6.234
R25.000
Wolfpack Gear
Dwg. #:
Nxt Asb:
Title: Middle Plate
Date:12/2/15
Scale: 1/2
Drwn. By: Savan Patel
Chkd. By:

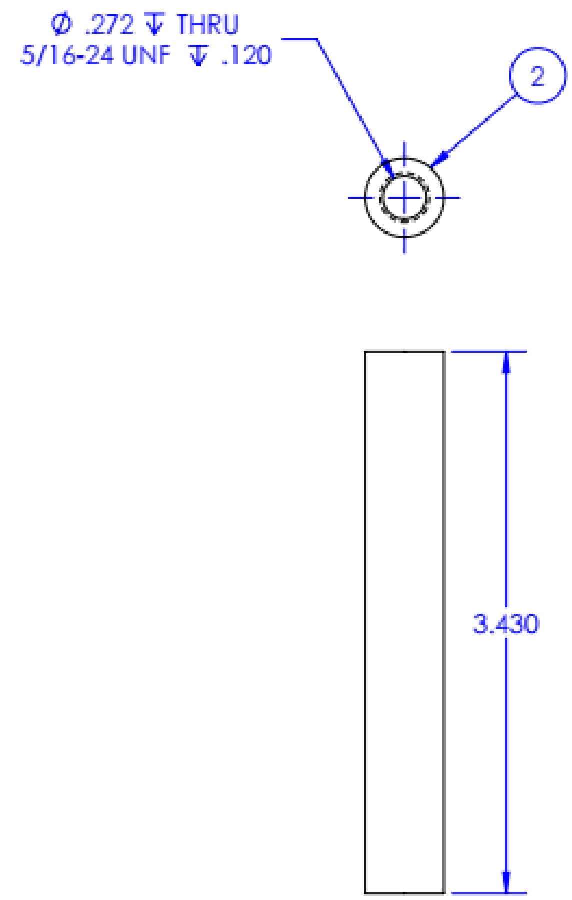


ITEM NO.
PART NAME
QTY.
1
Bottom Plate
1
NOTES:
1. ALL DIMS ARE INCHES
2. ALL TOLERANCES ±.010
3. BREAK SHARP EDGES
8.716
2.215
3.430
Ø .404
6.234
5.236
3.481
2.482
R25.000
Wolfpack Gear
Title:Bottom Plate
Drwn. By: Savan Patel
Dwg. #:
Nxt Asb:
Date:12/2/15
Scale: 1/2
Chkd. By:

ITEM NO.	PART NAME	QTY.
1	socket set screw	40

ITEM NO.	PART NAME	QTY.
2	Tapped Tube	20





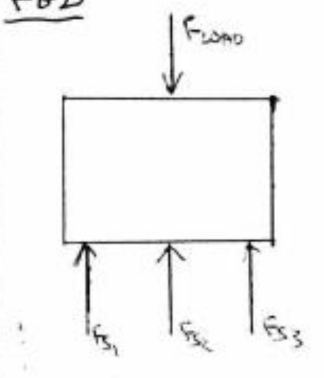
NOTES:
1. ALL DIMS ARE INCHES
2. ALL TOLERANCES ±.010
3. BREAK SHARP EDGES

Wolfpack Gear			Title:Small Parts		Drwn. By: Savan Patel
	Dwg. #:	Nxt Asb:	Date:12/2/15	Scale:	Chkd. By:

Appendix C: Detailed Supporting Analysis

Spring Constant | Team Wolfpack

FBD



$\sum F_y = 0$

$F_{S_1} + F_{S_2} + F_{S_3} = F_{load}$

Hookes Law: $F = Kx$

$K_1 x_1 + K_2 x_2 + K_3 x_3 = F_{load}$

Let $x_1 = x_2 = x_3$ same displacement

Let $K_1 = K_2 = K_3$ same spring

$3Kx = F_{load}$

Solve for K

$K = \frac{F_{load}}{3x}$

Generalize: $\boxed{K = \frac{F_{load}}{nx}}$ Spring constant for prescribed load and displacement and "n" number of springs.

Solve for K [lbs/in]

F = 45 lbs

x = 0.1875 lbs

n	K
2	120
3	80
4	60
5	48
6	40

n=2

$K = \frac{45\ lbs}{(2)(.1875\ in)}$

$K_2 = 120$ lbs/in

→ Select n=4, size a spring with a spring constant of 60 lbs/in.

Loading Case 1 | Team Wolfpack

- Load $\leq$ 45 lbs, spring system will hold the load.

<u>Known:</u> $x = 0.1875$ in, deflection gap in between plates

↳ sourced spring with $K = 60$ lb/in, 4 springs

$$P = Knx$$

$$45\text{ lbs} = (60\text{ lb/in})(4)(.1875\text{ in})$$

$$45\text{ lbs} = 45\text{ lbs} \checkmark$$ Springs are good.

→ the Load will be held by the threads

$P = 45$ lbs, multiply by 2 for dynamic load

. Use factor of safety of 2

↳ $\boxed{L_{applied} = 180\text{ lbs.}} \longrightarrow$ 4 springs $\longrightarrow \boxed{L'_{applied} = 45\text{ lbs.}}$ per spring

<u>- Threads/set screw -</u>

<u>Threads</u> - 5/16 - 24 UNF

<u>set screw</u> - 1/2 - inch steel

* Properties for threads taken from Shigley's Design book.

$L'_{app} = 45$ lbs
$A_t = 0.058$ in²/thread
$N = 24$ threads/in
$x = 1/2$ in

<u>find the total thread Area</u>

$$A_{total} = \underset{\text{length}}{x}\ \underset{\text{pitch}}{N}\ \underset{\text{thread area}}{A_t}$$

$$A_{total} = (1/2\text{ in})(24\text{ threads/in})(0.058\text{ in}^2/\text{thread})$$

$$\boxed{A_{total} = 0.696\text{ in}^2}$$

Loading Case 1		Team Wolfpack

find Applied Stress

$$\sigma_{Applied} = \frac{L_{App}}{A_{total}}$$

$$\sigma_{App} = \frac{45 \text{ lbs}}{0.696 \text{ in}^2} \longrightarrow \boxed{\sigma_{Applied} = 64.66 \text{ psi}}$$

- compared to the yeild stress of aluminum, the applied stress is three orders of magnitude less.

Loading Case 2 | Team Wolfpack

→ Load > 45 lbs, the plates touch, taking all of the Load.

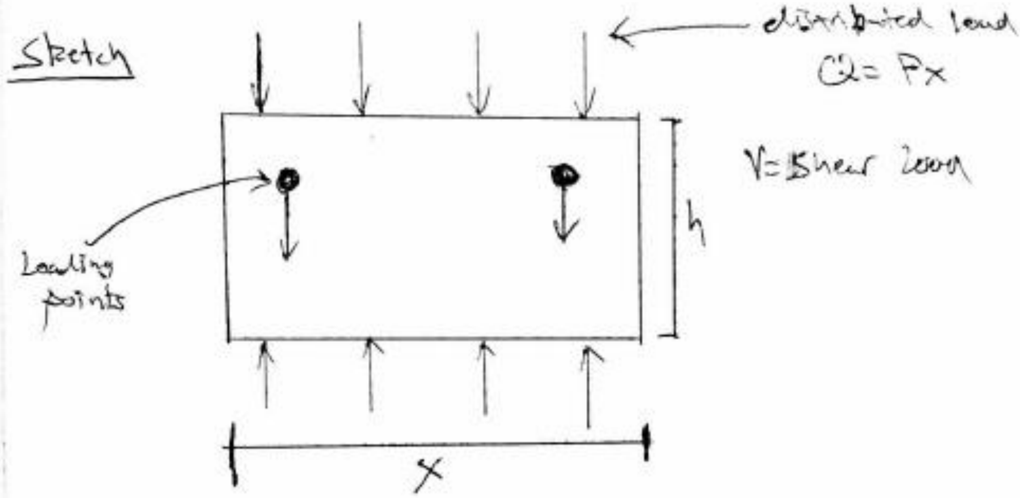
→ Analyze one plate, assume all plates take the same Load

→ assume plate is flat, plane stress only.

→ Only normal compressive load and in-plane shear.

↳ Include Shear to account for bending and torsion of the plate.

Sketch



- for worst case scenario, load in only shear and superimpose that case on an axially compressed case.

- for material properties, use data sheet from ME 412

↳ AS4/3501-6 Unidirectional Tape

$t_{ply} = 0.0052 in$ thickness

$V_f = 0.63$ fiber volume

$E_1 = 20$ Msi Longitudinal modulus

$E_2 = 1.4$ Msi transverse modulus

$G_{12} = 0.93$ Msi shear modulus

$\nu_{12} = 0.30$ Major Poisson's Ratio

Loading Case 2 | Team Wolfpack

Material properties continued

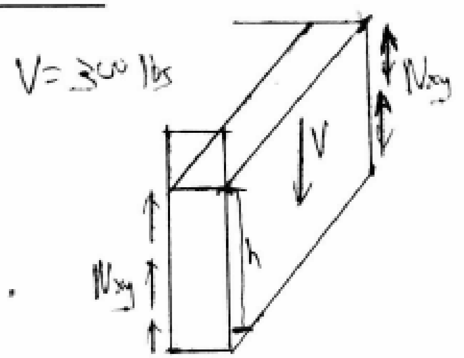
$\varepsilon_{1t}^{u} = 0.014$ $\quad \varepsilon_{1c}^{u} = 0.012$ $\quad$ ultimate strains

$\varepsilon_{2t}^{u} = 0.007$ $\quad \varepsilon_{2c}^{u} = 0.031$

Load-max = 75 lbs

$\to \quad \underbrace{75\,(2)}_{\text{dynamic}}\underbrace{(2)}_{\text{factor of safety}} = \boxed{300 \text{ lbs} = L_{applied}}$

Shear - Load comes through connection points



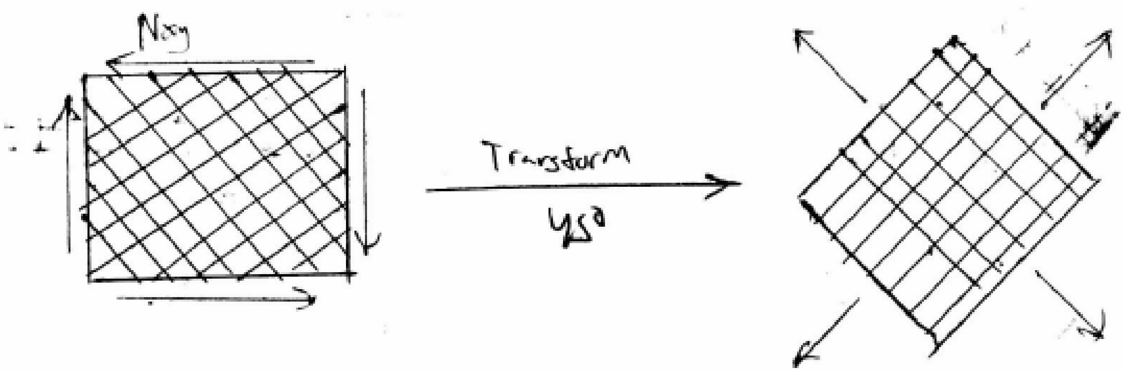
N_{xy} represents line loads

$\Sigma f_y = 0$

$-V + 2 N_{xy} H = 0$

$N_{xy} = \frac{V}{2H}$ lbs/in

- for shear we want to carry load w/ ± 45° fibers



Loading Case 2 | Team Wolfpack

- assumptions
- fibers take all load
- use compressive Ultimate strength
- 0.8 factor for pseudo A-basis Statistical safety factor

$$N_{ply} = E_1 (.8) (\varepsilon_{1c}^{u}) (t_{ply})$$

$$N_{ply} = (20e6\ psi)(.8)(.012)(.0052\ in)$$

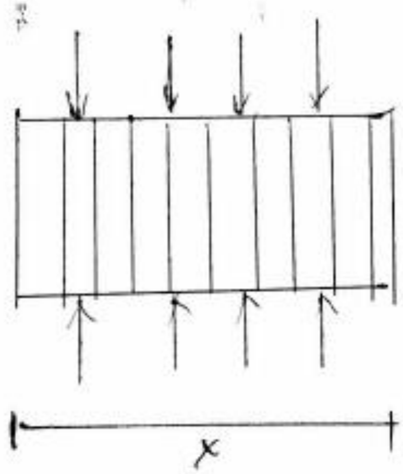
$$N_{ply} = 998.4\ lb/in$$

n = # of plies

$$n = \frac{N_{xy}}{N_{ply}} = 0.039\ \text{plies}$$

↳ 1 ply

Normal Compressive Load -



P = 300 lbs

x = 6 in

Q = 50 lb/in

$$N_x = \frac{P}{h} = 78.25\ lbs/in$$

- same material in 90° direction
- use same N_{ply}

$$n = \frac{N_x}{N_{ply}} = 0.07\ ply \rightarrow 1\ ply$$

Loading Case 2 | | Team Wolfpack

- Conclusion -

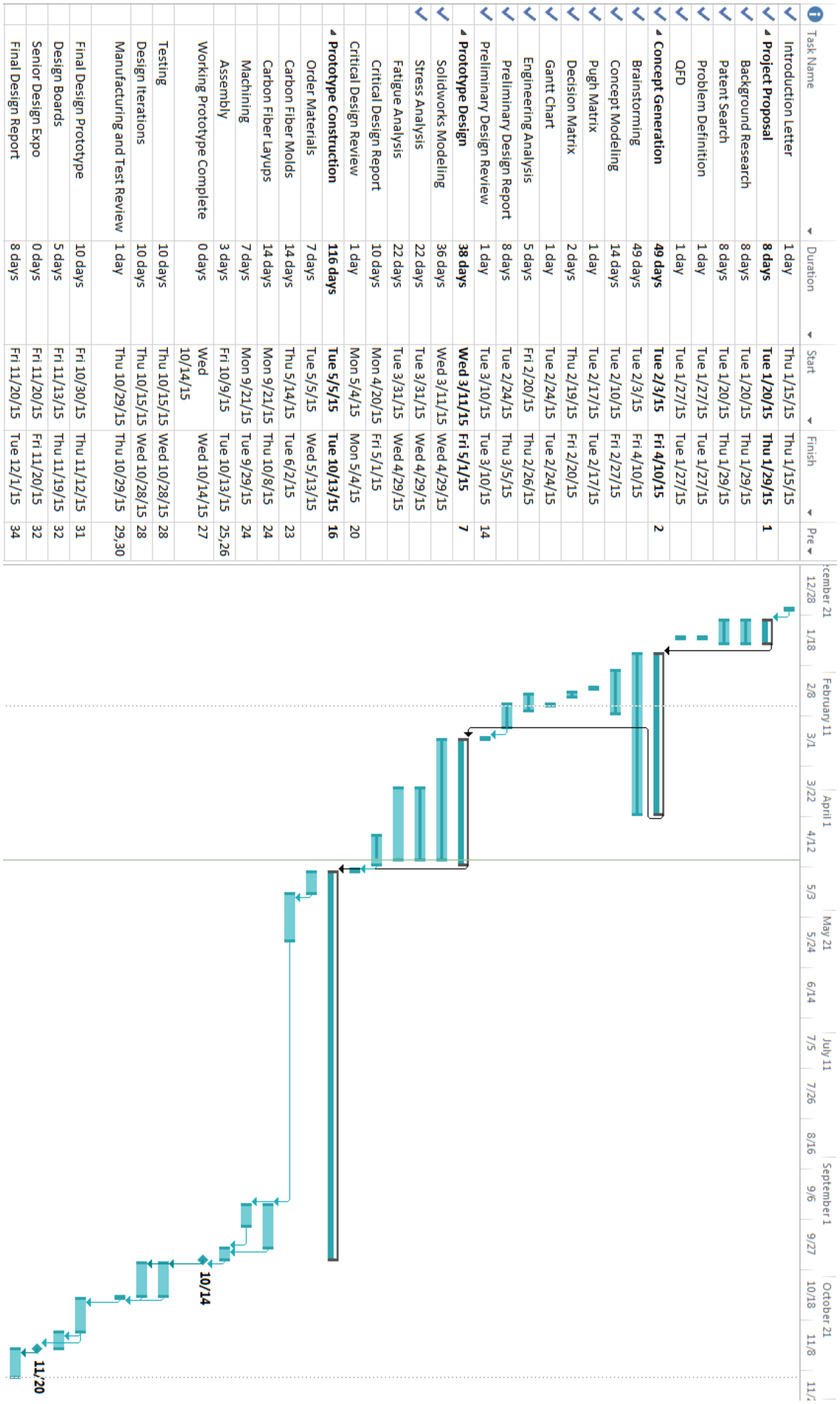
- Based on this rough calculation, the load is very small with respect to the strength of one ply of the considered material.

- for sake of the design

↳ $\boxed{[\pm 45, 90, 90, \pm 45] \rightarrow [\pm 45, 90]_S}$

↳ need to confirm this with Myles and Dr. Mello

Appendix D: Gantt Chart and Smart Sheet



Task Name	Duration	Start	Finish	Pre
Introduction Letter	1 day	Thu 1/15/15	Thu 1/15/15	
Project Proposal	**8 days**	**Tue 1/20/15**	**Thu 1/29/15**	**1**
Background Research	8 days	Tue 1/20/15	Thu 1/29/15	
Patent Search	8 days	Tue 1/20/15	Thu 1/29/15	
Problem Definition	1 day	Tue 1/27/15	Tue 1/27/15	
QFD	1 day	Tue 1/27/15	Tue 1/27/15	
Concept Generation	**49 days**	**Tue 2/3/15**	**Fri 4/10/15**	**2**
Brainstorming	49 days	Tue 2/3/15	Fri 4/10/15	
Concept Modeling	14 days	Tue 2/10/15	Fri 2/27/15	
Pugh Matrix	1 day	Tue 2/17/15	Tue 2/17/15	
Decision Matrix	2 days	Thu 2/19/15	Fri 2/20/15	
Gantt Chart	1 day	Tue 2/24/15	Tue 2/24/15	
Engineering Analysis	5 days	Fri 2/20/15	Thu 2/26/15	
Preliminary Design Report	8 days	Tue 2/24/15	Thu 3/5/15	
Preliminary Design Review	1 day	Tue 3/10/15	Tue 3/10/15	14
Prototype Design	**38 days**	**Wed 3/11/15**	**Fri 5/1/15**	**7**
Solidworks Modeling	36 days	Wed 3/11/15	Wed 4/29/15	
Stress Analysis	22 days	Tue 3/31/15	Wed 4/29/15	
Fatigue Analysis	22 days	Tue 3/31/15	Wed 4/29/15	
Critical Design Report	10 days	Mon 4/20/15	Fri 5/1/15	
Critical Design Review	1 day	Mon 5/4/15	Mon 5/4/15	20
Prototype Construction	**116 days**	**Tue 5/5/15**	**Tue 10/13/15**	**16**
Order Materials	7 days	Tue 5/5/15	Wed 5/13/15	
Carbon Fiber Molds	14 days	Thu 5/14/15	Tue 6/2/15	23
Carbon Fiber Layups	14 days	Mon 9/21/15	Thu 10/8/15	24
Machining	7 days	Mon 9/21/15	Tue 9/29/15	24
Assembly	3 days	Fri 10/9/15	Tue 10/13/15	25,26
Working Prototype Complete	0 days	Wed 10/14/15	Wed 10/14/15	27
Testing	10 days	Thu 10/15/15	Wed 10/28/15	28
Design Iterations	10 days	Thu 10/15/15	Wed 10/28/15	28
Manufacturing and Test Review	1 day	Thu 10/29/15	Thu 10/29/15	29,30
Final Design Prototype	10 days	Fri 10/30/15	Thu 11/12/15	31
Design Boards	5 days	Fri 11/13/15	Thu 11/19/15	32
Senior Design Expo	0 days	Fri 11/20/15	Fri 11/20/15	32
Final Design Report	8 days	Fri 11/20/15	Tue 12/1/15	34

Task Name	Start Date	End Date	Assigned To	Duration	% Complete
Senior Project Expo	**12/03/15**	**12/03/15**		**0**	
Mold Making	**09/30/15**	**10/12/15**		**9d**	**100%**
Finish Solidworks Drawing	09/30/15	10/05/15	savan.y.patel	4d	100%
G Code	09/30/15	10/05/15	savan.y.patel	4d	100%
Acquire Foam	09/30/15	10/05/15	savan.y.patel	4d	100%
Reserve Shopbot?	09/30/15	10/05/15	savan.y.patel	4d	100%
Make mold	10/02/15	10/12/15	savan.y.patel	7d	100%
Shopbot	10/02/15	10/05/15	savan.y.patel	2d	100%
Post Processing after shopbot	10/05/15	10/09/15	savan.y.patel	5d	100%
Coating	10/09/15	10/12/15	savan.y.patel	2d	100%
Machining Potted Inserts	**09/30/15**	**10/12/15**		**9d**	**100%**
Purchasing Tooling/material	09/30/15	10/09/15	sal.monforte@	8d	100%
Aluminum Rods	10/03/15	10/12/15		7d	100%
Cut to length	10/03/15	10/12/15	savan.y.patel	7d	100%
Bore through holes	10/03/15	10/12/15	all	7d	100%
Thread Ends	10/03/15	10/12/15	all	7d	100%
Set Screws	10/03/15	10/12/15	all	7d	100%
Bore 1/8" holes	10/03/15	10/12/15	all	7d	100%
Plate Fabrication	**10/05/15**	**10/21/15**		**13d**	**100%**
Layup	10/05/15	10/20/15		12d	100%
Carbon prep	10/05/15	10/13/15	sal.monforte@	7d	100%
Cutting	10/05/15	10/12/15	sal.monforte@	6d	100%
Weighing	10/13/15	10/13/15	all	1d	100%
Resin Setup	10/13/15	10/13/15	all	1d	100%
Vacuum Bagging	10/13/15	10/13/15	all	1d	100%
Wet Layup	10/14/15	10/20/15	all	5d	100%
Cure Time	10/14/15	10/20/15	all	5d	100%
Post Machining	10/20/15	10/21/15	all	2d	100%
Trim	10/20/15	10/21/15	all	2d	100%
System Assembly	**09/30/15**	**10/26/15**		**19d**	**100%**
System Design finalization	09/30/15	10/26/15		19d	100%
Determine available materials from Wolfpack	09/30/15	10/09/15	sal.monforte@	8d	100%
Sketch up design	09/30/15	10/09/15	darcilawrence	8d	100%
Spine	10/21/15	10/26/15		4d	100%
Plates	10/21/15	10/26/15	all	4d	100%
Hardware	10/21/15	10/26/15	all	4d	100%
Waistbelt	10/12/15	10/26/15	all	11d	100%
Attachment to spine	10/12/15	10/26/15	all	11d	100%
Sewing	10/12/15	10/26/15	all	11d	100%
Load Attachment to plates	10/12/15	10/26/15	all	11d	100%
Shoulder Straps	10/12/15	10/26/15	all	11d	100%
Connection to spine	10/12/15	10/26/15	all	11d	100%
Padding	10/12/15	10/26/15	all	11d	100%
Sewing	10/12/15	10/26/15	all	11d	100%
Testing	**10/21/15**	**11/20/15**		**23d**	**100%**
Individual plate testing	10/21/15	10/30/15	sal.monforte@	8d	100%
Talk to Dr. Mello about using Composites Lab	10/21/15	10/30/15	sal.monforte@	8d	100%
Composite lab tests	10/21/15	10/30/15	sal.monforte@	8d	100%
System Testing	10/27/15	11/20/15		19d	100%
Ergonomic testing	10/27/15	11/20/15	all	19d	100%
Load attachment points	10/27/15	11/20/15	all	19d	100%
Padding	10/27/15	11/20/15	all	19d	100%
Loading scenarios	10/27/15	11/20/15	all	19d	100%
Report/Poster	11/20/15	12/01/15		8d	100%
Write Report	11/20/15	11/30/15	all	7d	100%
Manufacturing	11/20/15	11/30/15	all	7d	100%
Testing	11/20/15	11/30/15	all	7d	100%
Results	11/20/15	11/30/15	all	7d	100%
Conclusion	11/20/15	11/30/15	all	7d	100%
Print Report	12/01/15	12/01/15	all	1d	100%
Make Poster	11/20/15	11/30/15	all	7d	100%
Print Poster	12/01/15	12/01/15	all	1d	100%