California Polytechnic State University

Cal Poly Sit Ski

Final Report

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1. Introduction

This is the Final Report, a description of the final design iteration of the Cal Poly Sit Ski. The design, build, and test phases of the project have been completed. The following sections detail each of these phases of the project.

1.1 Our Project

The purpose of this project was to design, build, and test a Sit Ski for the US Adaptive Ski Team. The design is for Mr. Marlon Shepard, a new competitor on the Ski Team, who is in need of a new racing sit ski. Some of the top design priorities include reduced weight, increased rider comfort, and increased durability over existing designs. With these design considerations in mind, our team from Cal Poly designed, built and tested a cross country sit ski in June 2010 at the mechanical engineering senior project expo.

The project was sponsored by a National Science Foundation grant written by Dr. Brian Self of the Mechanical Engineering Dept. and Dr. Kevin Taylor of the Kinesiology Dept. at California Polytechnic State University, San Luis Obispo. We also worked closely with Mr. Jon Kreamelmeyer, the Developmental Coach of the US Adaptive Ski Team to determine the needs and goals of the project.

In order to develop a design that meets the client's needs, we drew upon experience of past Cal Poly senior project sit skis, available commercial designs, and background research regarding spinal injuries. The project goal was to create a satisfactory design that meets the client's needs in the given timeline.

We have been working with Mr. Kreamelmeyer and Mr. Shepard to develop the final design for the sit ski based on specifications and targets generated from our Quality Function Deployment (QFD) matrix. From the concept generation phase, the bucket concept was selected and further developed. The design description gives much more detail and insight into the final design.

1.2 Our Team

Our team, Cal Poly Sit Ski, is comprised of three senior mechanical engineering students. We are excited about the project and all have unique interests that make us a well-rounded team.

David Bydalek is originally from Minnesota, and cross country skied as a child. He has experience machining, welding and enjoys fixing cars in his spare time. Marc Bergreen enjoys winter sports including ice climbing and backcountry skiing. His experience with composite materials and Finite Element Analysis were valuable design resources. Ross Gompertz enjoys the outdoors, races bikes in his spare time and has considerable experience in fabrication that proved to be beneficial throughout the process.

2. Background

To gain further understanding of the project, each member of the team researched several different topics. We looked into the physiology of spinal cord injuries to better understand how a person with a spinal injury would utilize the sit ski. We also looked into the sport of cross country skiing to see how the sit ski would be used in competition. Then we looked into past sit ski senior projects and commercially available sit skis to gain understanding of the current designs. Being knowledgeable of the existing products has helped us create a benchmark for our design and will hopefully allow us to create a design that is better than what is currently available.

2.1 Physiological Background

The spinal cord is a bundle of nerves that runs down the middle of the back surrounded by the vertebrae that make up the human spinal column. Its job is to transfer signals between the body and the brain. When the cord is damaged badly enough as a result of traumatic injury or disease there is loss of function (paralysis) below the level of injury. Injuries higher up on the spine will result in greater disability.

Figure 1. Body parts affected by injuries at various locations on the spinal column [2].

The severity of a spinal cord injury is based on two criteria: the location of the injury and the amount of the cord that is damaged at that location. The amount of damage determines whether the injury is classified as either partial or complete. A complete spinal cord injury results in total loss of function in all body parts below the point of injury while a person with a partial spinal cord injury may retain some sensation or movement below the point of injury [1].

The term paraplegia is used to describe the loss of motion and feeling in the lower half of the body while the loss of function in everything below the neck is known as quadriplegia. See Figure 1 for a diagram of the body parts affected by injuries at various levels. There are about 450,000 people living in the United States with spinal cord injuries and about 10,000 new injuries every year [2].

This information will help us to determine how much our sit ski must support and restrain the athlete. For example, athletes with injuries to the thoracic nerves (see Figure 1) may be unable to use their abdominal muscles, and would require much more support than athletes capable of using their core. The physiological information also helped us to understand the biomechanics of the movements required to propel a sit ski; allowing us to create a design that will be comfortable yet still light and fast.

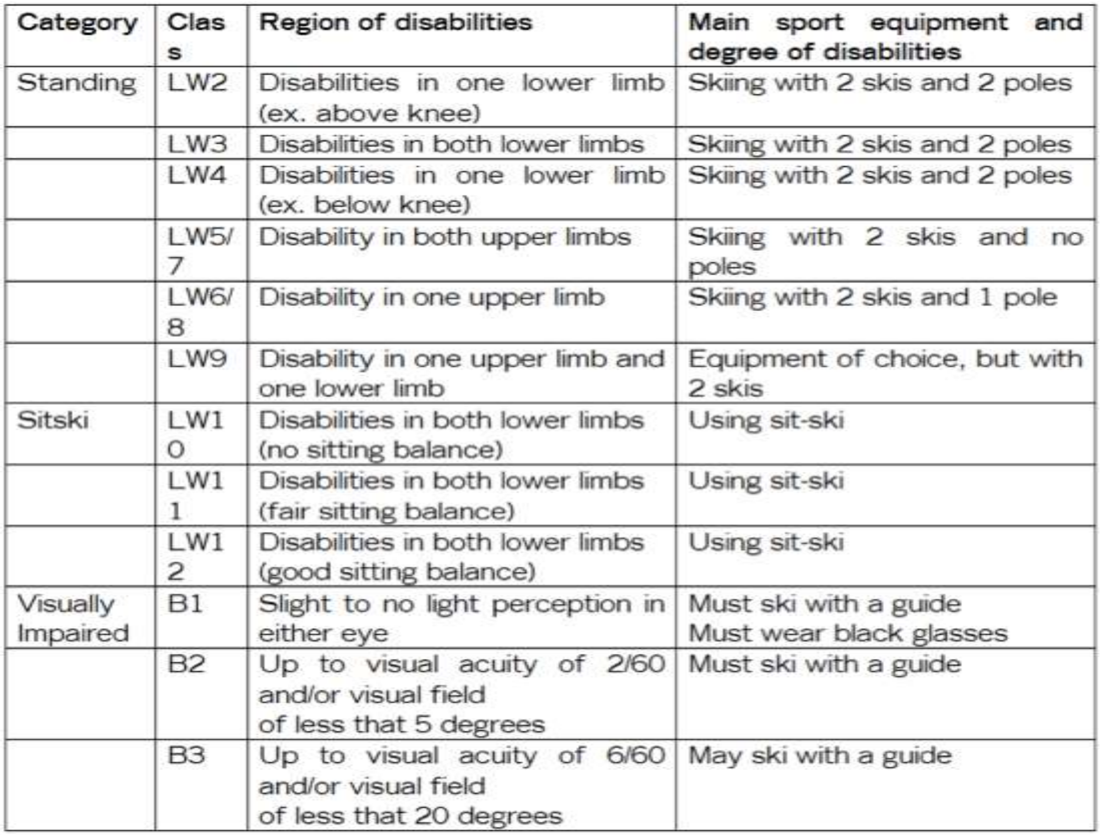
Other physiological considerations include spasticity and pressure sores. Spasticity is the involuntary movement of one's muscles. These involuntary muscle movements occur because the muscle is no longer in contact with the brain. Therefore these signals are not regulated by the brain, and thus feedback is not sent to the muscle resulting in spastic movement [3].

Pressure sores are another possible injury that can develop from use of the sit ski. A pressure sore is an injury to the skin, and the tissue underneath of it. This occurs when blood supply to one's tissue is cut off for an extended period of time. This effectively kills the tissue where the pressure sore is located. If left untreated, the sore can go below the skin and start to deteriorate the muscle near the sore [4].

2.2 The Sport of Adaptive Cross Country Skiing

The main governing body for the sport of adapted cross country skiing is the International Paralympic Committee (IPC). This organization determines the rules for the sport. Before competition, the IPC uses a series of tests to divide up the athletes into different sport classes based on their disability. See Table 1 for a break down and explanation of the sport classes [5]. The sit ski races range in total length from long 15 km courses to 2.5 km sprints, but the longer races are broken up into multiple laps on a shorter course. See Table 2 for the course lengths approved by the Paralympic Committee for the sit ski classes (LW10-12). Due to the athlete's disabilities in these categories, the courses are generally constructed to limit the number of steep hills and sharp corners [4].

Table 1. Sport classes recognized by the Paralympic Committee (Appendix V).



Category	**Class**	**Region of disabilities**	**Main sport equipment and degree of disabilities**
Standing	LW2	Disabilities in one lower limb (ex. above knee)	Skiing with 2 skis and 2 poles
	LW3	Disabilities in both lower limbs	Skiing with 2 skis and 2 poles
	LW4	Disabilities in one lower limb (ex. below knee)	Skiing with 2 skis and 2 poles
	LW5/7	Disability in both upper limbs	Skiing with 2 skis and no poles
	LW6/8	Disability in one upper limb	Skiing with 2 skis and 1 pole
	LW9	Disability in one upper limb and one lower limb	Equipment of choice, but with 2 skis
Sitski	LW10	Disabilities in both lower limbs (no sitting balance)	Using sit-ski
	LW11	Disabilities in both lower limbs (fair sitting balance)	Using sit-ski
	LW12	Disabilities in both lower limbs (good sitting balance)	Using sit-ski
Visually Impaired	B1	Slight to no light perception in either eye	Must ski with a guide Must wear black glasses
	B2	Up to visual acuity of 2/60 and/or visual field of less that 5 degrees	Must ski with a guide
	B3	Up to visual acuity of 6/60 and/or visual field of less that 20 degrees	May ski with a guide

Table 2. Course length and total race distance for sit ski classes [4].

Event	Course
15 km	7.5 km, 5 km or 3.75 km
10 km	5 km or 3.33 km
7.5 km biathlon	2.5 km
5 km	5 km or 2.5 km
2.5 km	2.5 km
Relay	2.5 km

The LW10-12 classes are authorized to compete on sit skis. These consist of light, form-fitted frames and seats mounted to standard cross country skis that allow the athletes to pole themselves along with their upper body. The frame and seat of the sit ski are mounted onto the skis using either standard cross country ski bindings, custom proprietary mounts or a combination of the two. The IPC does not put any restrictions on the geometry of sit skis other than that the bottom of the seat must be less than thirty centimeters above the tops of the skis. However this restriction has begun to lose its merit due to a wide range of athlete heights. There are very few restrictions on the types of equipment that can be used (such as ski's and binding systems) and any issues that arise are treated on a case-by-case basis.

2.3 Past Senior Project Designs

Cal Poly students have built several different sit skis for various clients with different goals in mind. There have been several adjustable sit skis built to help athletes find the ideal skiing position and one project fabricated with a carbon fiber leaf spring frame. The objectives of each of these designs have been slightly different and we hope to utilize all of the knowledge gained to make our design satisfactory for our client.

Figure 2. Cal Poly sit ski designs: Ski Lynx on the left carbon leaf spring design in the middle and the modular CP sit ski design on the right (equipped with roller skis for testing on pavement). (Barats)

2.3.1 Adaptive Cross Country Sit Ski – Ski Lynx, 2009

The goal of this project was to update the Modular Paralympic Sit Ski built in 2008 with an improved seat design, as well as design, build, and test an entirely new design. Both designs were intended to be adjustable and accommodate various seat positions. The main objectives of this project were to create a new adjustable seat, design a new frame, develop a comfortable seat, and incorporate safety devices to help restrain the user. This project succeeded in the areas of frame design and seat comfort but failed to meet the adjustability specifications, weight requirements, and budget target. The team fell short of their goal of five in of vertical adjustability, went over the 10 lb weight goal, and went over the $1000 budget. Despite these setbacks, the project seemed successful and created a quality sit ski in addition to improving the design from the previous year [6].

The Adaptive Cross Country Sit Ski was comprised of welded aluminum tubing, a carbon fiber seat base, foam, and vinyl seat covering. The design was with the legs stretched outward in front of the rider. It had some components that may be valuable in our design. The carbon fiber seat base provided a lightweight seat that is also very strong. The aluminum tubing was a good choice but it might be better to select a higher grade aluminum (Grade 7075 instead of 6061) to get more strength per weight and reduce the weight of the frame. Because our design doesn't have to be adjustable, the weight of the sit ski is less than this design [6].

2.3.2 Modular Paralympic Sit Ski – CP Sit Ski, 2008

The Modular Paralympic Sit Ski was designed to be a highly adjustable design that would accommodate several different seat positions for a wide range of athletes. The US Paralympic Team would use this adjustable sit ski to find their optimum skiing position before they had a custom ski built to their specifications. The main design goals were adjustability, multiple seat position options, lightweight, and comfort [7].

The final design consisted of telescopic aluminum tubing combined with a carbon fiber seat pan and backrest. The leg rest out front supported the legs with a fabric sling to put your feet in. This team met their requirements of adjustability although it was not as easy as they had expected. They also went over budget and the final product was heavier than expected. Additionally, the seat design was not adequate and was found to be flimsy. It did not provide support to people with higher levels of paralysis. Also, the padding was determined to be too hard and uncomfortable. The feedback from people who have used this design will be helpful in our design. Evaluating the padding on this ski will help us understand what levels of cushion users are seeking. [7].

2.3.3 Carbon Leaf Springs

The Carbon fiber leaf spring design was completed as a Master's Thesis for a Graduate student. The intent of the design was to provide a shock absorbing effect for a smoother ride and to attempt to create a steering mechanism from the bend twist coupling of the carbon fiber frame.

The design consisted of two large C shaped strips of carbon fiber attached to the skis and a small carbon fiber seat pan. This design was innovative but ultimately unsuccessful. In order to transfer power effectively, riders often need a rigid frame. This design did not provide enough support for athletes with higher levels of paralysis and was not very comfortable because the seat lacked sufficient padding. Due to the flexibility in the carbon fiber springs and lack of cross members, the skis wandered and the glide that is crucial to maximizing efficiency was negatively affected. Although this design was very lightweight and original, it was not as effective as intended [8].

This project provided insight into the use of composite materials in our design. It illustrates the lightweight capability in the design and how simple it can be if the number of parts is minimized. The design also proved the importance of a rigid frame to maximize glide and power transfer.

2.4 Current Commercially Available Skis

Most high-end racing-oriented sit skis are made custom for the individual rider but there are a few companies that make high quality production sit skis that can be used by many different riders. There are two main companies that dominate the American market for sit skis: Spokes ‘n Motion, and Sierra Sit Skis. Spokes ‘n Motion is a large adaptive sports equipment manufacturer based out of Denver, CO. They make many products ranging from sailing equipment to ice hockey sledges. Spokes ‘n Motion currently produces two sit ski models: the Kiwi, and the Prashberger. Sierra Sit Skis, owned and operated by Michael Byxbe is a much smaller operation, but the skis are known for their high quality and lightweight frames.

2.4.1 Spokes ‘n Motion Kiwi:

Designed for racing or just exploring in the snow, the Kiwi is versatile and highly adjustable, allowing it to be fitted properly to many different athletes. It also uses standard cross country ski bindings, making it easy to change skis and eliminating the need for an expensive proprietary binding system. However, at 12 lbs, the Kiwi is a bit heavier than several other skis on the market.

STANDARD FEATURES	- Frame : made of light weight aircraft quality aluminium - Weight without skis: 12 LBS (5,5 kgs) - Adjustable footrest - Sling/Fabric style seat - Leg support - Attachements for tether lines - Compatable with standard cross country ski bindings (recommended : Salomon SNS profile bindings) - Recommended standard cross country skis (approx.180 cm length)
SIZES	- XL (seat width: 17" or 44 cm) - Adult (seat width: 14" or 36 cm) - Junior (seat width: 12" or 31 cm)
COLOURS	- Polished aluminium
OPTIONS	CUSTOMIZED and FITTED AT YOU SIZE AND NEED - Seat width and height - Footrest set at requested length - Leg support fixed at requested height

Figure 3. Spokes 'n Motion Kiwi specifications [A].

2.4.2 Spokes ‘n Motion Praschberger:

The Praschberger is a more stripped-down racer than the Kiwi yet still adjustable enough to accommodate athletes with different body and injury types. The Praschberger is two pounds lighter than the Kiwi but not compatible with standard cross country ski bindings and is so low to the ground the rider must use specially angled ski poles.

Figure 4. Spokes 'n Motion Praschberger [B].

STANDARD FEATURES	- Front seat frame tapered inwards - Super light chrom-moly tube frame - Weight: approx.10 LBS (4,5 kgs) - Seat angle as required - Special angled ski poles Measurement without skis : length: 33-39" (85-100 cm) width: as seat width height: 16-24" (40-60 cm)
SIZES	- Seat width: 13" (34 cm) 14" (36 cm) 15" (38 cm) 16" (40 cm) 17" (42 cm) 18" (44 cm) - Back height: 11" (30 cm) 13.5" (35 cm) 16" (40 cm) or as required
COLOURS	- Frame : black, dormant red - Seat and back support: black - Different colours and options available
OPTIONS	- Special back height available

Figure 5. Specification sheet for the Spokes 'n Motion Praschberger [C].

2.4.3 Sierra Sit Skis:

Sierra Sit Skis produces fewer skis than Spokes ‘n Motion, but each one of their high quality skis is produced with a specific athlete in mind. This eliminates the need for significant adjustability, allowing the skis to be much lighter (down in the seven pound range) and more form-fitting. They also use specially molded and padded bucket seats instead of cloth sling style seats. The weight of the Sierra Sit Skis will be the most difficult specification for our team to match.

Figure 6 Sierra Sit Ski built by Michael Byxbe [D]

2.5 Frame Materials

There are a number of different materials that could be used to make the frame of the sit ski. Aluminum tubing is lightweight but not as stiff as steel. It can be more challenging to weld and sometimes requires heat treatment to relieve residual thermal stresses. Steel tubing is heavier than aluminum but stronger. If the design is primarily stiffness driven, steel tubing could be a viable choice. Steel is available in very thin walled tubing sizes than can have comparable strength to weight ratio of aluminum while remaining stronger. The frame design could also have composite tubes which are very strong, stiff, and lightweight. Although very lightweight, durability and manufacturability present concerns for composites. All of the existing designs for sit skis currently employ either a steel or aluminum frame.

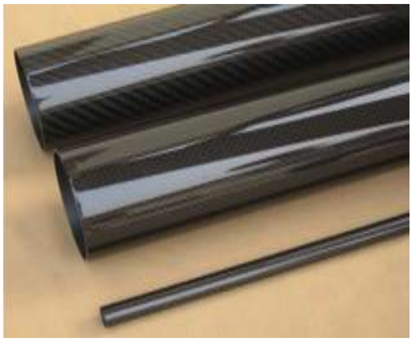


Figure 7 Carbon fiber tubes that could be used for the frame [E].

2.6 Seat Materials

The seat of the ski is a crucial component that is heavily influenced by the material selected. The stiffness, strength, and weight of the seat must be balanced to create a comfortable design that is strong enough to hold the athlete but flexible enough to conform to the athlete. It cannot have pressure points or rubbing and must withstand the impact of a fall or collision. Material choice is greatly influenced by the comfort and feel of the seat.


Figure 8 Fiberglass cloth that could be used for the seat [F].

Some materials considered included carbon fiber, fiberglass, natural fiber composite, and molded plastic. Each of these materials could be custom molded into a shape that conforms to the athlete. Carbon fiber has the highest strength and stiffness to weight ratio which makes it a good choice in terms of weight. Carbon fiber would be relatively easy to manufacture but is very expensive. Fiberglass is slightly less strong and stiff but is substantially less expensive than carbon fiber. Both carbon and fiberglass could have issues with splintering when they fail causing the user to get splinters from the seat. A good resin system could help alleviate this problem.

Natural fiber composites and molded plastics also seem like viable materials for the custom seat. Natural fiber composites are lightweight, strong, and more environmentally friendly than other thermoset composites. Hemp fiber composites are available commercially and are used by a


Figure 9. Hemp cloth composite that could be used for seat [H].


Figure 10. Sintra, moldable plastic that could be used for the seat [G].

local surfboard shaper in Morro Bay, CA. These hemp composites are not quite as strong as other composites (like fiberglass or carbon) and would be slightly heavier. Moldable plastic would make a good material for the seat because it could be flexible while still remaining strong. Additionally, moldable plastic does not cause injuries from splinters like natural fibers could. Because of our manufacturing limitations, it is important to find a plastic that can be built with limited tooling. Other designs have used injection molded plastic but because this is not available, a material such as Sintra can be used [G]. Sintra is a heat moldable plastic available in sheets that could be shaped into seat. It is flexible when heated and then holds its shape after cooling.

2.7 Foam and padding materials

The seat needs to be padded to eliminate any edges or pressure points. There are many options for this foam from common sleeping pad material available in any outdoor store to more exotic specialty foams. At the suggestion of Dr. Taylor, Ethafoam was chosen for use in padding the seat of the ski. This is a very high quality foam made by Dow and can be supplied by the Kinesiology department here on campus.

2.8 Restraints

We looked at different methods of restraining the athlete but the best and most cost effective method will be to use padded backpack straps and wide (3 to 4 in.) nylon webbing. The wide webbing straps will distribute the pressure over a wider area on the athlete’s body decreasing the chance for hot spots or rubbing. These straps are readily available at our local outdoor stores.

3. Design Development

3.1 Objectives

The overall objective of this project is to design, build, and test a sit ski for Mr. Marlon Shepard that is useable for International Paralympic Competition. The design is aimed at maximizing Marlon’s strengths of competition and most importantly, it is designed specifically for his body.

3.2 Customer Needs

Quality Function Deployment (QFD) is an aid that our team has employed to help create engineering specifications from the customer’s wants and needs. The customer’s needs are put into a weighted matrix (which can be found in Appendix A), from which engineering specifications are developed and quantified. The matrix also allows us to rate competing designs based on our customer requirements. We have rated the three previous sit skis developed at Cal Poly on a 1-5 scale to see how well they met our customer’s needs. Another advantage of the QFD is that it allows the user to see interdependence of design specifications. Some of these interdependencies include seat height and restraint systems; and sharp edges, pressure points and restraints.

3.3 Specifications

After developing the QFD, design specifications are developed. Table 2 below shows our design requirements in order of importance based on QFD rankings. The table also shows the relative risk level of accomplishing the target and how the parameters will need to comply with the targets. Risks are designated as High Risk (H), Medium Risk (M) and Low Risk (L). Compliance is designated by Analysis (A), Inspection (I), Similarity (S), and Testing (T). Parameters that need requirements are in blue font, while parameters that pose a high risk are in red font.

Table 3. Cal Poly Sit Ski Design Specifications.

Spec #	**Parameter Description**	**Requirements**	**Units**	**Tolerance**	**Risk**	**Compliance**	**Weighted QFD Total**
1	Time to Manufacture	200	Hours	Max	M	I	179
2	Seat width	13	Inches	Min	L	I	171
3	Seat length	20	Inches	Max	L	I	171
4	Seat depth	16.5	Inches	+/-0.25	L	I	171
5	Seat height from top of skis	30	Centimeters	Max	L	I, S	166
6	Restraints	50	Lbs	Min	M	A, I, S, T	122
7	Weighs less than	10	Lbs	Max	H	A, S, T	115
8	Vertical ski deflection	0.5-1	Inches	Max	M	A, I, T	110
9	Number of sharp edges	0	Number	Max	L	I	93
10	Number of pressure points	0	Number	Max	L	A, I, S, T	93
11	Horizontal angular ski deflection	2	Degrees	Max	M	A, I, T	82
12	Cost less than grant money allotted	1500	Dollars	Max	H	I, S	72
13	Track width	0.25 Bilateral Tolerance	Inches	Range	L	I, S	64
14	Time to attach self to sit ski	5	Minutes	Max	M	I, S, T	48
15	People required to secure rider (including rider)	1	Number	Max	L	I, S, T	44
16	Angular ski roll	5	Degrees	Max	L	A, I, T	41
17	Time to remove skis	1	Minutes	Max	M	A, I, S, T	27

Our top 3 requirements all relate to holding Marlon's torso secure. The targets were determined by Mr. Shepard and agreed upon by Cal Poly Sit Ski. The next important design requirement is the seat height. According to our QFD this is nearly as important as securing Marlon's torso. The importance of the requirement makes sense since seat heat will directly affect power transfer to the rider. Seat height will also play a role in the rider's feeling of stability and the ability to right oneself after a fall. It is interesting to note that the weight of the sit ski did not show up higher in our specifications list, but it will heavily drive design and materials selection of the sit ski.

3.3.1 High risk Specifications

In most timed competitions weight is a key to success. Nordic skiing is no exception to the norm. The less the sit ski weighs, the less weight that the rider has to carry in the race. Thus, lighter weight could lead to faster race times. The target weight of 10 lbs maximum is a hard goal to accomplish. Two of the three previous designs at Cal Poly failed their weight requirements, so we will have a challenge. Meeting the requirement means that the sit ski is one of the lightest ones out there. The other high-risk target is keeping the sit ski under budget. The main concern for the budget is that making something light, but strong generally costs quite a bit, and 1 of 3 previous teams at Cal Poly failed to meet their budget.

3.4 Method of Approach

Our method of approach to this project was to break it down into three phases, design, build, and test. From there, each phase will have components that are outlined in the Gantt chart in Appendix B. The design phase of the project began with the identification of needs. This came directly from the client and was translated into a list of technical specifications and engineering targets through the QFD process described above. With technical specifications to work towards, we moved to the concept development phase. After generating numerous concepts in a brainstorming session, we refined our ideas and choose the five concepts presented below. At this point, we have received input from Mr. Kreamelmeyer and Mr. Shepard to help us finalize the design. A thorough analysis of the final design has been completed and the details are presented in the following sections.

The procurement and the manufacturing phase of the project followed the design stage. After the completion of fabrication, sit ski was tested. In the test phase, we evaluated the final product against our list of specifications and determined if the product meets the client's needs.

3.5 Concepts

The concepts described below were developed during several brainstorming sessions combined with our background research and sponsor input. A variety of ideas were generated, each with different frame shapes, seat designs, and material selections. The strengths and weakness of each of the concepts is explained in detail along with sketches of each design.

3.5.1 Space Frame

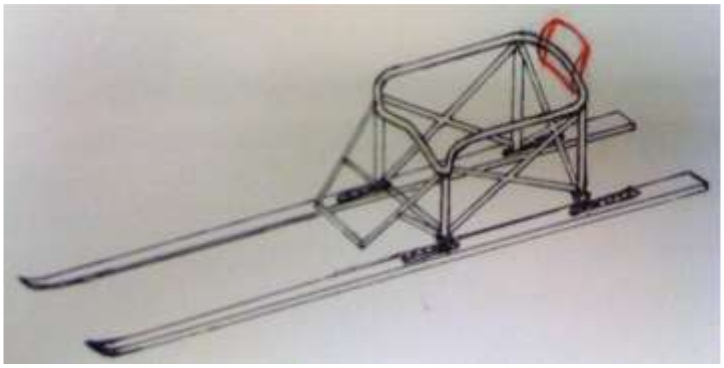


Figure 11. Space Frame concept design sketch. Composed of welded aluminum tubing and a cloth seat (not shown).

This design was inspired by the lightweight tubing design of bicycles. A minimal amount of tubing would be used to create a very lightweight and rigid frame. A lightweight nylon fabric would be attached to the frame to create a comfortable and conforming seat. The advantage of the Space Frame is its lightweight components and rigidity. Some difficulties may arise with manufacturing the aluminum frame. Because of the majority of the members in the frame are welded together, it would likely have to be heat treated to reduce the residual thermal stresses. This is often an expensive process and may not be within our budget constraints. This design would also require extensive custom fixtures to ensure that the frame remains straight. Additionally, the cloth seat may not be as supportive as other types of seats causing the user to lose power transfer as the seat flexes. The frame would mount with dual NNN bindings. This binding system allows the skis to flex and conform to the terrain because they are mounted on two pins. A rigid fixture would tend to force the skis to remain straight instead of allowing this flexibility.

3.5.2 Bucket

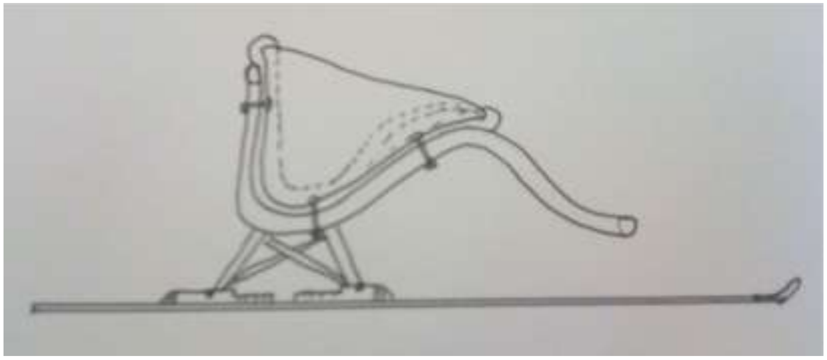


Figure 12. Bucket concept design sketch. Aluminum frame with a plastic seat padded with foam on the inside.

The Bucket concept is similar to the space frame but has a slightly different shape and seat. The main frame tube would be a bent aluminum tube shaped around a molded plastic seat. The seat would be shaped to fit the athlete and padded with foam to reduce pressure points. Below the bent tube frame and plastic seat, a truss support frame would provide a rigid mount to the skis. Dual NNN bindings would provide the same flexibility as described for the Space Frame. The main disadvantage of the Bucket is its weight. Although still relatively lightweight, the plastic would not be as lightweight as a fabric seat. Depending on the exact shape and weight distribution in the final design, vibration of the front foot rest could also present a problem for the Bucket. Manufacturing a high quality plastic seat that fits Mr. Shepard without creating pressure points could also present challenges.

3.5.3 Mountain Cruiser

The unique design of the Mountain Cruiser is very different from other concepts. It incorporates a bent frame that allows the weight to be behind the front bindings. With this design, one binding could be used to connect to each ski. A lightweight frame would support a composite seat to make the design relatively lightweight. The frame would require a safety mechanism to keep the frame and seat from pivoting forward on the front binding. Some challenges of this design are the large stress concentration at the bend in the frame and finding the ideal flex in the frame. Ideally the ski would have some flexibility but not lose power transfer do to “bobbing up and down.”

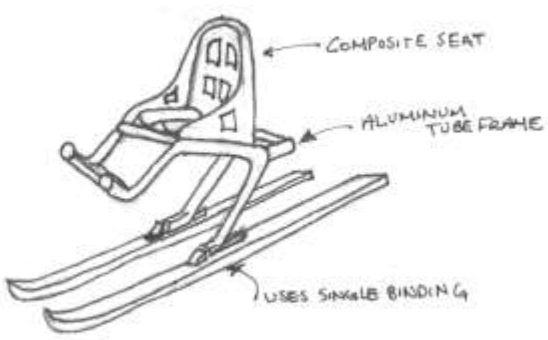


Figure 13. Mountain Cruiser concept design sketch.

3.5.4 Carbon Fiber Uni-body

Inspired by the lightweight and innovative carbon fiber products available in the bike industry, the Carbon Fiber Uni-body shown in Figure 14 is a complete one piece design. Because the seat and frame are integrated into one piece, it can be much lighter. Additionally the carbon fiber material can be optimized to create a very strong, stiff, and lightweight sit ski. The only downsides to the Carbon Fiber Uni-body are its challenging manufacturing and expensive material. This design could also present challenges because the analysis of the carbon fiber would be difficult and if it fails, the failure will be catastrophic. From a safety standpoint this design may not be the best choice because of the variability of the strength depending on how well it is manufactured.

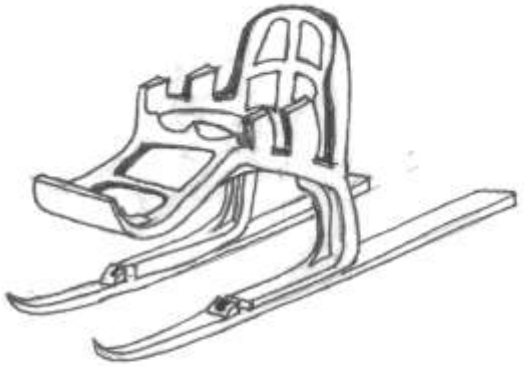


Figure 14. Carbon Fiber Uni-body concept design sketch. Frame and seat are built with one integrate carbon fiber design.

3.5.5 Cloth Bucket

The Cloth bucket shown in figure 15 is

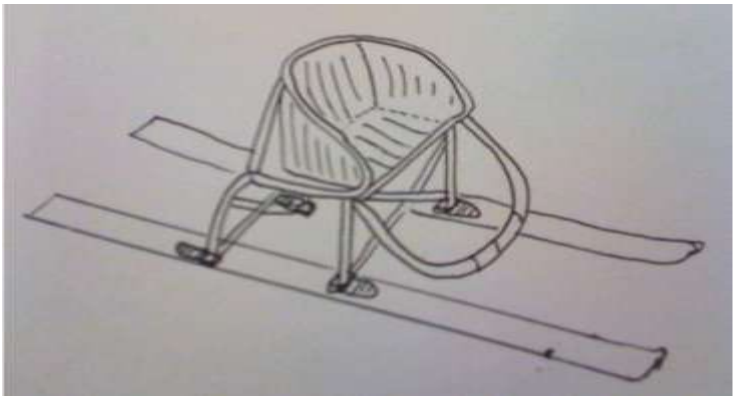


Figure 15. Cloth Bucket concept design sketch. Cloth seat is attached to thin wall steel tubing frame.

similar to the Bucket design except with a cloth seat. The concept was to have a tailored fabric seat that conforms to the athlete’s body. A thin wall steel tubing frame would support this seat. Although steel is heavier than aluminum, it can be manufactured with very thin walls to reduce weight. Steel is also much stiffer than aluminum making it a good choice when deflection and vibrations are a problem. Additionally, the frame would be easier to manufacture because steel can be easily welded and does not need to be heat treated. When compared to other seat designs, the cloth seat would not be quite as conforming and it may feel wobbly creating issues with power transfer. This design would also be inexpensive and easy to manufacture.

3.6 Design Process

Our team has been following Ullman’s Mechanical Design Process for this project. Figure 16 below illustrates the process well. The first two columns on the left side of the figure illustrate the steps that were taken to develop our Project Proposal. Notice that the bottom of the second column illustrates the specification approval. Since these concepts were approved, we were able to move on to the conceptual design stages. As mentioned in the Method of Approach section on page 15, we had brainstorming sessions and concept evaluations to narrow down our ideas to the five concepts in the previous section. We then refined the plan by comparing these concepts in a decision matrix (shown in Table 4). If the concepts are approved then we will continue to the right and start product development. Lastly, notice that the figure has a circular motion to it, meaning that there is no straight line to design. Iteration and refinement is necessary in every step of design [9].

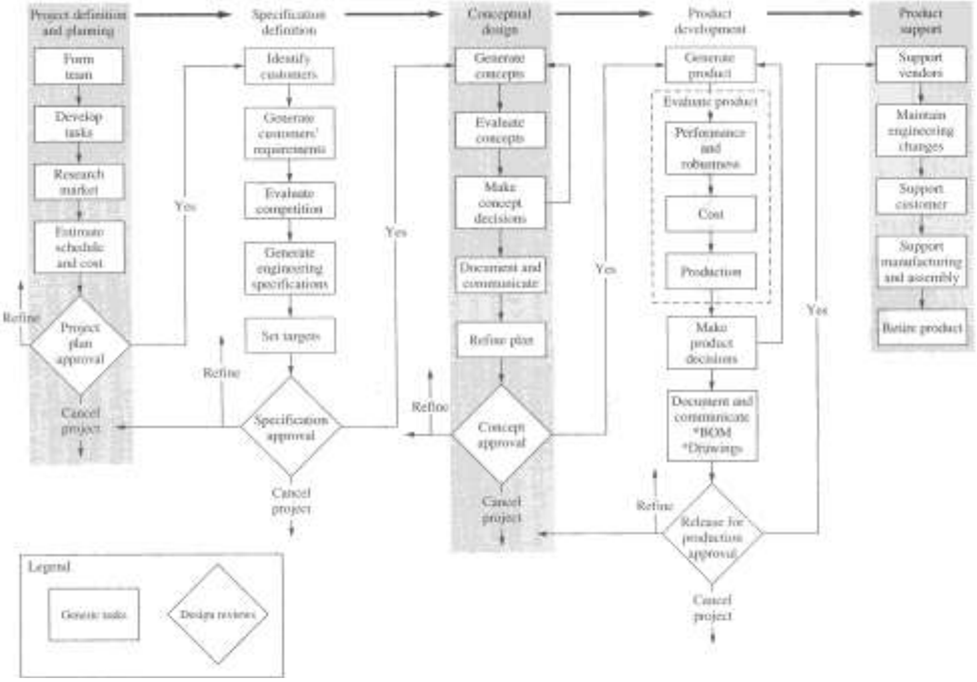
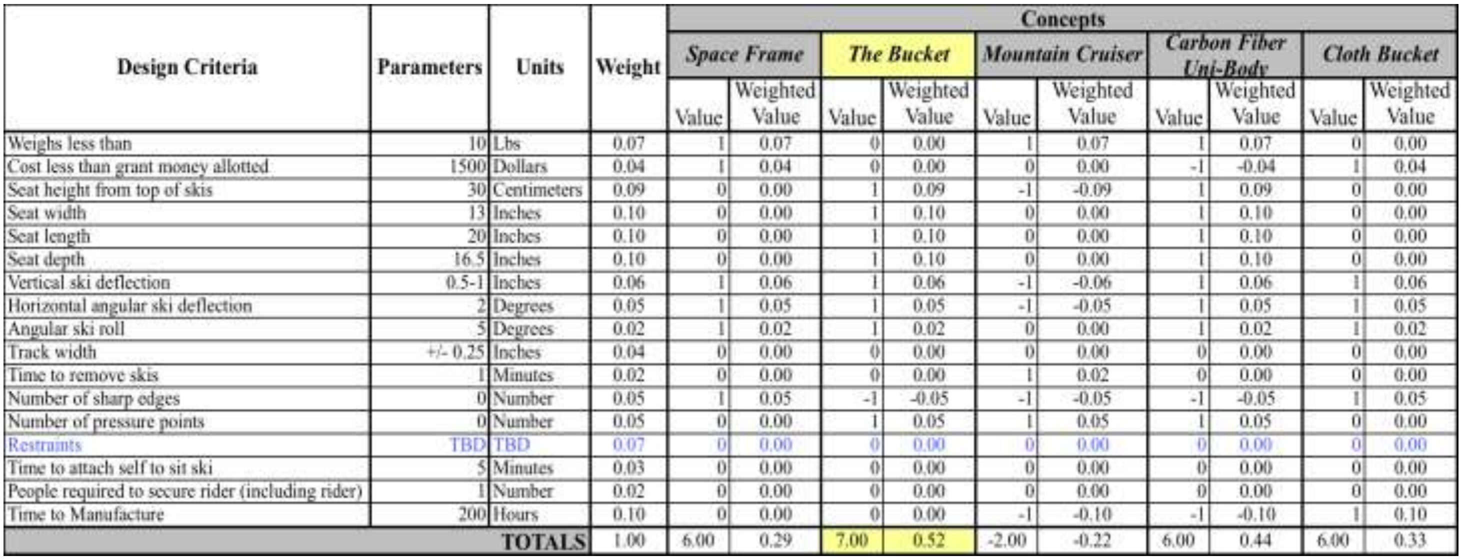


Figure 16 Ullman’s Mechanical Design Process flowchart illustrates the different steps necessary to complete a design. These steps are always subject to refinement and iteration [9].

One way to refine concepts is by use of a decision matrix. To develop the matrix, we normalized the totals of all the engineering requirements from the QFD so that the weight would add to one, thus making the math simpler for analysis. The five concepts were then evaluated against the requirements and the Sierra Sit Ski (chosen as the datum). If the concepts were evaluated as better than the datum they received a 1. If the Sierra Sit Ski met the requirement better, the concept received a -1 and if both the datum and the concept equally met the requirement then the concept received a 0. These numbers were multiplied by the corresponding weight to get the weighted values. The weighted values were then added up to get a total value for each concept. *The Bucket* concept scored the highest in the decision matrix, followed by the *Carbon Fiber Uni-Body*.

Table 4. Decision matrix for sit ski concepts. The winning design was *The Bucket* which is highlighted in yellow, followed by the *Carbon Fiber Uni-Body* design. The Restraint requirement is highlighted in blue because it was still TBD at the time the decision matrix was created.



Design Criteria	**Parameters**	**Units**	**Weight**	**Concepts**									
				Space Frame		***The Bucket***		***Mountain Cruiser***		***Carbon Fiber Uni-Body***		***Cloth Bucket***	
				Value	Weighted Value	Value	Weighted Value	Value	Weighted Value	Value	Weighted Value	Value	Weighted Value
Weighs less than	10	Lbs	0.07	1	0.07	0	0.00	1	0.07	1	0.07	0	0.00
Cost less than grant money allotted	1500	Dollars	0.04	1	0.04	0	0.00	0	0.00	-1	-0.04	1	0.04
Seat height from top of skis	30	Centimeters	0.09	0	0.00	1	0.09	-1	-0.09	1	0.09	0	0.00
Seat width	13	Inches	0.10	0	0.00	1	0.10	0	0.00	1	0.10	0	0.00
Seat length	20	Inches	0.10	0	0.00	1	0.10	0	0.00	1	0.10	0	0.00
Seat depth	16.5	Inches	0.10	0	0.00	1	0.10	0	0.00	1	0.10	0	0.00
Vertical ski deflection	0.5-1	Inches	0.06	1	0.06	1	0.06	-1	-0.06	1	0.06	1	0.06
Horizontal angular ski deflection	2	Degrees	0.05	1	0.05	1	0.05	-1	-0.05	1	0.05	1	0.05
Angular ski roll	5	Degrees	0.02	1	0.02	1	0.02	0	0.00	1	0.02	1	0.02
Track width	+/- 0.25	Inches	0.04	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Time to remove skis	1	Minutes	0.02	0	0.00	0	0.00	1	0.02	0	0.00	0	0.00
Number of sharp edges	0	Number	0.05	1	0.05	-1	-0.05	-1	-0.05	-1	-0.05	1	0.05
Number of pressure points	0	Number	0.05	0	0.00	1	0.05	1	0.05	1	0.05	0	0.00
Restraints	TBD	TBD	0.07	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Time to attach self to sit ski	5	Minutes	0.03	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
People required to secure rider (including rider)	1	Number	0.02	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Time to Manufacture	200	Hours	0.10	0	0.00	0	0.00	-1	-0.10	-1	-0.10	1	0.10
		TOTALS	1.00	6.00	0.29	7.00	0.52	-2.00	-0.22	6.00	0.44	6.00	0.33

4. Final Design

The final design utilizes a combination of the bucket and space frame concepts using an aluminum frame and an injection molded plastic seat. We have chosen these materials based on their lightweight, strength and availability. Our design can be roughly broken down into four components: the frame, seat, bindings, and restraints. These components are labeled in the full assembly view of our current design (Figure 17).

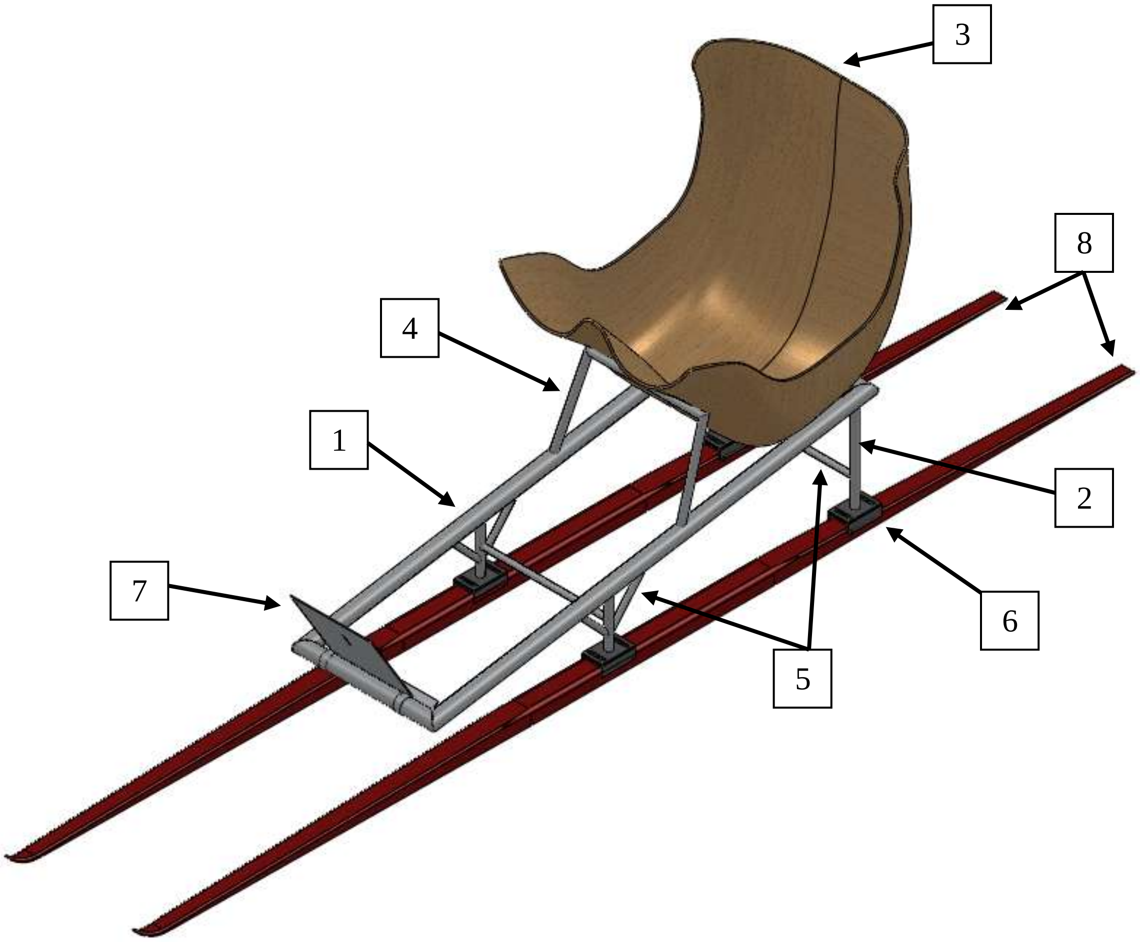


Figure 17. Sit Ski Final Design Components. 1. Main frame tubing (two mirrored sections). 2. Back vertical support legs. 3. Plastic injection molded seat. 4. Front seat support. 5. Cross members. 6. Binding "feet". 7. Foot plate. 8. Skis

4.1 Frame

Figure 18. Current frame design.

The frame we uses three different tubing sizes, allowing us to construct a sit ski that is as light and as strong as possible. The main tube frame (1) is 1 in. diameter, the vertical support legs (2) and seat support (4) are 0.5 in. diameter, all remaining tubing (5) is 0.375 in. diameter. The 1” and 0.5” tubing have a 0.049” wall thickness. While the 0.375” tubes have a wall thickness of 0.035 in. Instead of using tubing bends or welds we tried to eliminate joints wherever possible, decreasing the chance of stress concentrations and failures at the joints. Our final analysis (both the finite element analysis and the hand calculations) shows that heat-treat of the frame will not be necessary after welding. The heat treatment increases the strength of the aluminum by reversing the changes in the metal caused by welding but is very expensive and difficult to perform without warping the frame. The tubing will all be 6061-T6 aluminum. We expect the tubing to go back to 6061-0 after welding and then gain equivalent strength of 6061-T4 after it age hardens for 3-4 months. More description on allowable yield strengths and the stress in the tubes can be found in the Analysis section. Our frame design can be seen in Figure 18. The detail drawings are located in Appendix C.

4.2 Seat

The bucket seat is constructed from injection molded plastic. The seat was supplied by Enabling Technologies, LLC. This is the same type of seat used by the Sierra Sit Ski. Its flexible thigh portion allows the seat to cup the rider’s upper legs as the leg restraints are tightened. The seat has been padded and trimmed to create a customized, anatomical fit. See the picture of our chosen seat in Figure 19. The seat is bolted to the frame using four bolts: two at the bottom rear of the seat, and one connecting each leg trough into the frame’s thigh support.

Figure 19. Picture of our seat. (To be supplied by Enabling Technologies LLC) [D]

4.3 Bindings

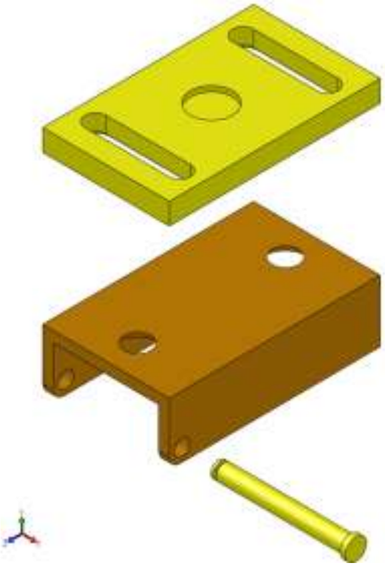


Figure 20. Binding "feet".

After the frame and seat, the third element of our design is the binding system. Our sit ski uses two NNN bindings on each ski. They face in opposite directions to keep the skis rigidly attached to the frame. The part of the frame that interfaces with the bindings are the "feet" made from aluminum C – channel machined to hold the body of the binding just like a regular ski boot. These eliminate nearly all lateral play in the bindings and are be bolted to the frame in slots to allow for different track widths. Once the bindings have been properly aligned and the track width has been adjusted, attaching and detaching the skis will be fast and easy. The use of the bindings requires the user to open the bindings, drop the frame in and flip the bindings closed. No additional tools are required. We want the skis to rigidly attach to the ski throughout its life and not loosen with age. This has been accomplished by using a pin that connects the frame to the bindings on the skis replaceable. This will allow the athlete to replace the pins if they become bent. Aside from checking that the fasteners on the frame are tight, this is hopefully the only maintenance and repair necessary during the life of the sit ski. See Figure 20 for an isometric view of the binding "feet" that will be bolted to the frame.

4.4 Restraints

The final element of our design is the restraints, which hold the rider in the sit ski. They consist of 2" wide nylon straps for the seat, and a 1" wide nylon strap to secure the feet to the foot plate. The larger nylon straps used on the seat use large plastic buckles to secure Mr. Shepard's thighs to the sit ski. The foot plate has the 1" nylon strap riveted to it so that Marlon can secure his feet to the sit ski. An additional nylon strap has been riveted to the footplate and attached to the back seat support so that Mr. Shepard can pull his legs tight when spasticity occurs. This will effectively stretch his calves and allow the spasticity to subside. The layout of the restraints can be seen in figure 21 on the following page.

Figure 21. Layout of restraints showing three straps: two thigh straps, and an ankle strap.

5. Technical Content

5.1 Analysis

The analysis performed on the sit ski mainly focused on the strength of the frame. Because we are purchasing proven seat and bindings, analysis is not needed for these components. The initial hand calculations performed on the frame were rough engineering estimates. The structure is highly indeterminate and challenging to analyze with traditional methods. Hand calculations were used to gain an understanding of how the structure responds to loads; a more detailed finite element analysis would help give a more accurate prediction of the strength of the frame.

5.1.1 Hand Calculations

To ensure the sit ski will be strong and lightweight a thorough analysis must be completed. The stress, deflection, vibration of the frame must be closely analyzed to locate any sources of failure or ways in which the frame would fail to meet the project specifications. The hand calculations were performed on a frame similar to that of a sierra sit ski. This gave us a good idea of what loads might be applicable for the design our ski. This simple analysis by hand allowed us to determine what loads we wanted to apply to a more detailed finite element analysis. Hand calculations were performed to determine the following parameters:

1. Deflection at Footrest
2. Stress on the Footrest
3. Natural Frequency on Footrest
4. Stress Analysis at Seat Support Joint
5. Forward and Backward Deflection of Vertical Supports
6. Shear and Bearing Stress on Binding Pin
7. Fatigue Strength of the Footrest

The hand calculations for each case are attached in Appendix D. Each of the locations of the analysis on the frame is annotated in Figure 22 below.

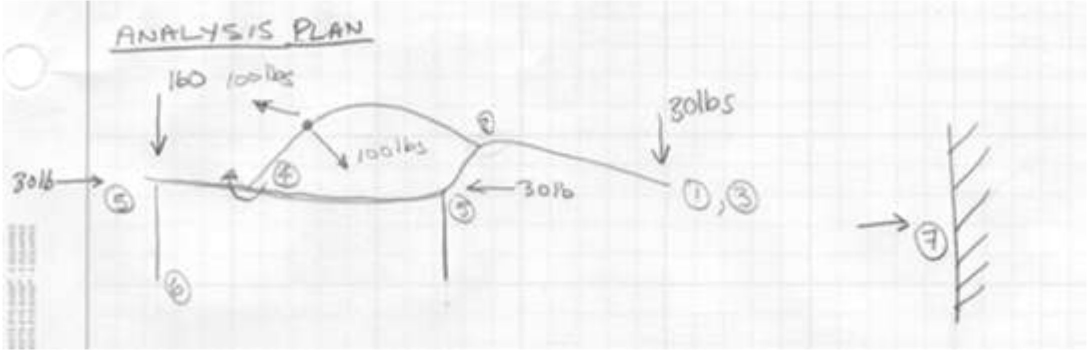


Figure 22. Diagram showing locations of specific hand calculation analysis.

Because the frame is statically indeterminate with a very irregular loading, it had to be simplified to complete hand calculations. The frame was broken into pieces and analyzed separately as statically determinant components. The key assumptions for each of the analyses are described below.

5.1.1.1 Deflection at Footrest

The footrest was analyzed with beam theory as a fixed cantilever beam with a 30lb tip load applied at an angle of 33 degrees from the normal. It was assumed that the footrest was fixed at the joint where the seat supports meet the foot support tubes. With this assumption, the tip deflection due to this load was 0.292in (tube specifications: aluminum 0.75 in. diameter, 1/16 in. wall thickness).

5.1.1.2 Stress on the Footrest

The stress at the footrest support due to the same load as case one was also analyzed with beam theory. For this analysis, 0.75in, 1/16 in. wall thickness tubing was used. Direct shear was neglected and the bending stress in the tube was calculated to be 27,200 psi with the equation $\sigma = \frac{Mc}{I}$. This load is significant because the allowable yield stress for 6061 aluminum ranges is 45,000psi. This gives a factor of safety of 1.6

5.1.1.3 Natural Frequency on Footrest:

The natural frequency of the vibration of the footrest was calculated to determine how the footrest would respond to free vibration. A distributed mass cantilever beam with fixed end condition was found to have a first natural frequency of 446 hz. This is much higher than the expected frequency of vibration, approximately 2 hertz, that the ski will experience.

5.1.1.4 Stress Analysis at Seat Support Joint:

The point where the bent seat supports join the main frame will be areas of high stress. The loading was modeled as an alternating 50 lb load on each support through the bolt that connects to the seat. The stresses at these joints were approximated by cutting the bent support where the seat bolts will go through them and then modeling the two separate pieces as cantilevered beams. The 50 lb alternating load was then applied to both members. One of these beams carried mainly axial compression and tension, while the other supported transverse loads. The piece in compression and tension was analyzed with the basic stress equation:$\sigma = \frac{P}{A}$. The resulting stresses in this member were only about 370 psi which is far below the yielding stress of 6061 aluminum (45,000 psi). The other member which saw transverse loading was analyzed using the beam theory equation: $\sigma = \frac{Mc}{I}$ and the stresses were found to be about 18.6 ksi. Both of these members were assumed to be 0.75 in. diameter tubing with 1/16 in. wall thickness.

5.1.1.5 Forward and Backward Deflection of Vertical Supports:

To approximate the forward and backward deflection of the vertical seat supports (the rear "legs" on the sit ski) we modeled them as cantilevered beams, fixed at the bindings and applied a 30lb alternating load to the top where the rear of the seat will be bolted in. The deflection was then calculated using the equation for the maximum deflection in a cantilevered beam: $\delta_{max} = \frac{Pl^3}{3EI}$. The maximum deflection for aluminum tubing with 0.75 inch diameter tubing with 1/16 in. wall thickness was calculated to be 0.0637 inches (approximately 1/16 in.).

5.1.1.6 Shear and Bearing Stress on Binding Pin:

We conducted two separate analyses on the pin. The first was calculating the direct shear on one cross section of the pin loaded vertically with 160 lbs using the shear stress equation: $\tau = \frac{P}{A}$ and the stress was found to be only about 6500 psi even though this loading case is quite conservative. The second analysis was calculating the bearing stress on the holder of the pin (again assuming a vertical 160 lb load) using the equation: $\sigma = \frac{P}{A}$. The bearing stress worked out to be 5100 psi. The low magnitude of both of these values gives us confidence that our pins will not fail in the bindings.

5.1.1.7 Fatigue Strength of the Footrest:

The riders feat bouncing up and down on the footrest as he/she rides causes a cyclic load on the footrest. This cyclic load causes fatigue of the aluminum. A fatigue analysis was performed to determine the life of the footrest. A Modified Goodman fatigue analysis determined that the footrest would withstand 1 million cycles with a safety factor of 5.5. This gives us confidence that the footrest will not fail in fatigue.

5.2 Analysis – Finite Element Analysis (FEA)

Because of the simplicity of the hand calculations and assumptions needed, further analysis was necessary to determine how the components of the frame interact. A Finite Element Model (FEM) was developed to understand the interaction of each of the welded members. The frame was modeled with beam elements in a 3D wire model. Section properties for each of the different tubing sizes were applied to the beam elements so the stress throughout the frame could be determined. For boundary conditions, all degrees of freedom were restrained at the 4 binding connections. Several load cases, shown below in Figure 23, were developed from Marlon's weight and the maximum expected force on the frame to determine the factor of safety on failure.

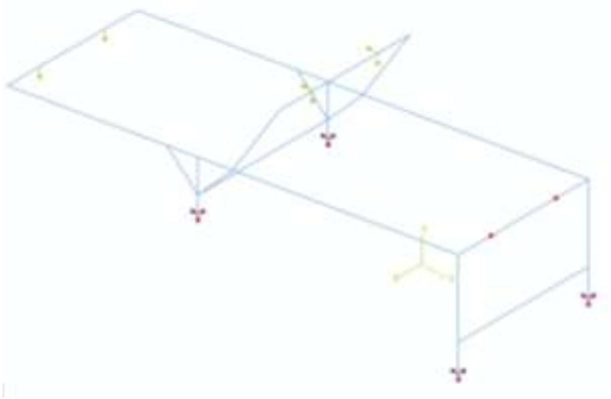


Figure 23A Pushing forward on seat at start of pole stroke.

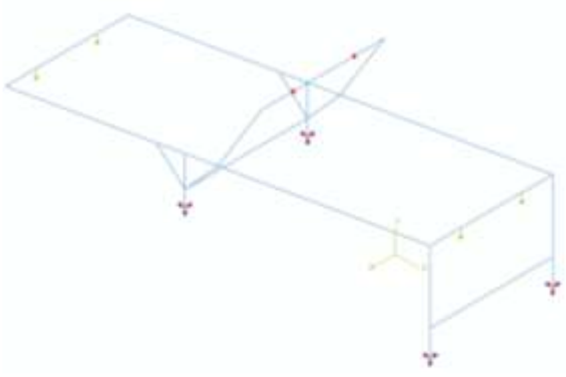


Figure 23B Pushing back on seat at end of pole stroke.

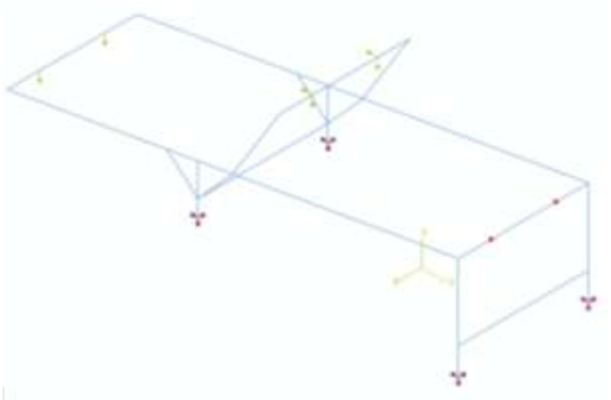


Figure 23C. Similar to load case A. Offset load on frame seat support and footrest; 70lbs forward and down on seat support right, 30lbs forward and down on seat support left, 40lbs down on footrest right, 10lbs down on footrest left.

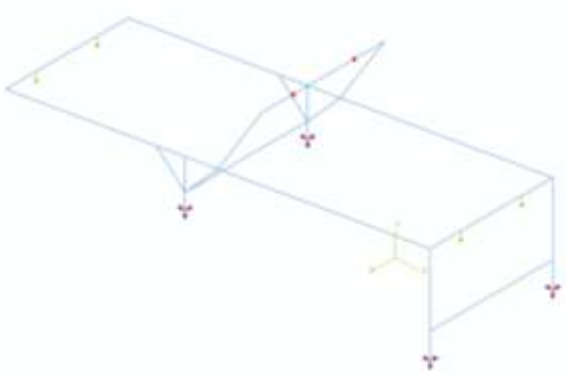


Figure 23D. Similar to load case B. Offset load on rear of frame and seat support. 150lbs down on right rear, 90lbs down on left rear, 40lbs down on footrest right, 10lbs down on footrest left.

The results generated from the FEA were compared with the hand calculations to verify the findings. This should help verify the accuracy of the FEA model.

5.2.1 High Stress Areas

Of the four load cases shown, several locations of high stress were identified. The front uprights had significant stress during the load case shown in Figure 23C. That plot of the Von Mises stress from this case is shown in Figure 24.

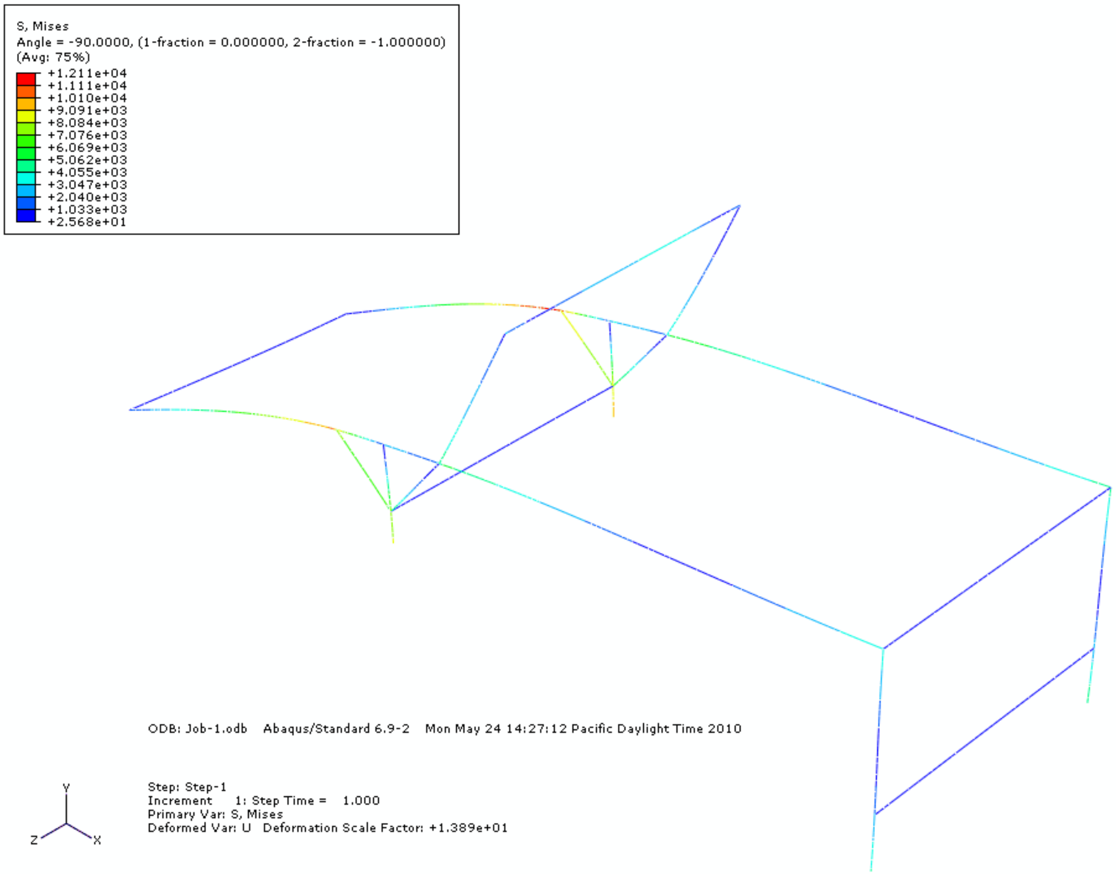


Figure 24. Von Mises Stress in the frame from load case shown in Figure 23C. The max stress occurs in the bend of the footrest support. The max stress is approximately 12kpsi.

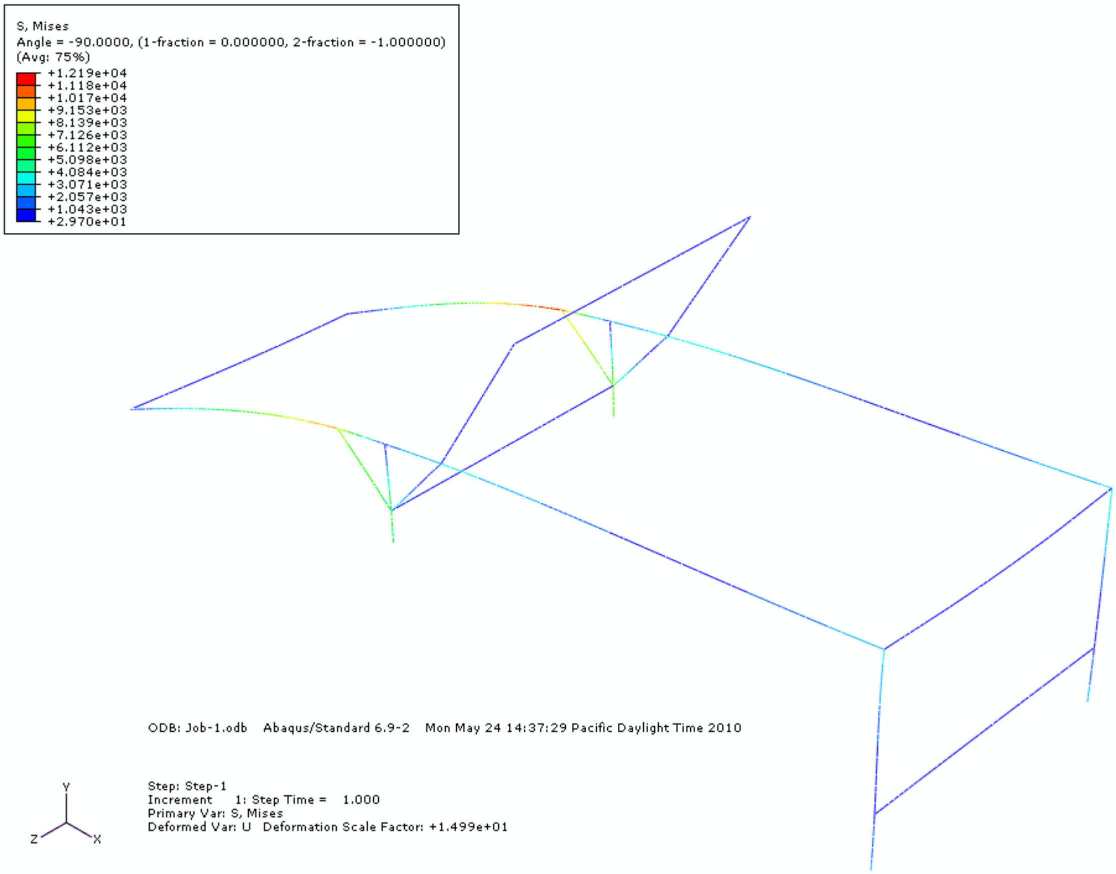


Figure 25. Mises Stress in the frame from load case shown in Figure 23D. The max stress occurs in the bend of the footrest support. The max stress is approximately 12kpsi.

The FEA analysis of the frame shows that the max stress in the frame will be 12kpsi. This stress occurs in the main frame tube in front of the front upright assembly. This value is far below the 6061-T6 Aluminum allowable, however, the strength of the tubing will be reduced when it is welded. The 6061-T6 will become 6061-0 (annealed state). After it is welded, the strength will fall to approximately 18kpsi however, age hardened will occur during a 3 week period following the welding. Some strength will be gained back and the final yield strength is expected to be approximately 25kpsi. This gives a final safety factor of 2. This will create a lightweight, strong, and safe design.

6. Manufacturing

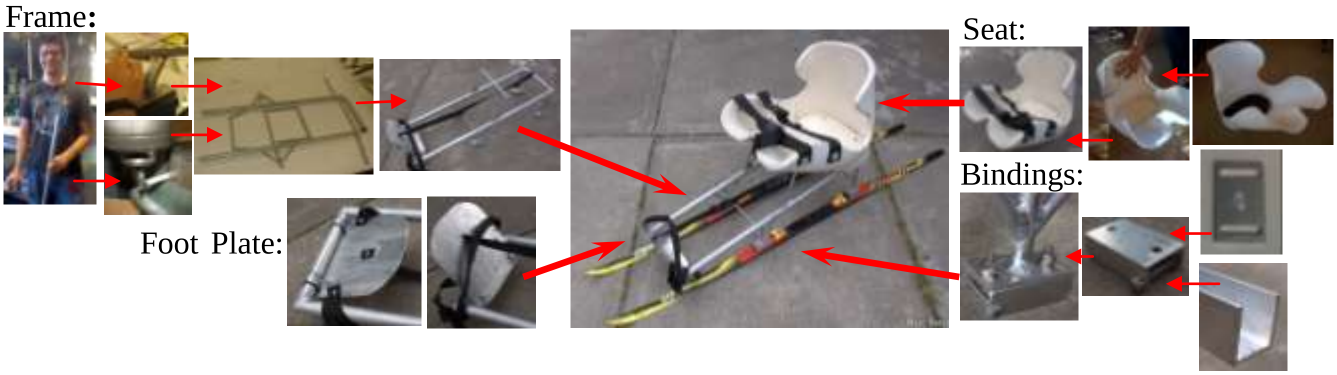


Figure 26. Diagram of the four main manufacturing tracks: the frame, seat, bindings and foot plate. The final assembly is shown in the middle.

6.1 Fabrication Methods

Manufacturing of the Sit Ski began with the frame (the upper left track in figure 26 above). Each of the frame members were cut to length and mitered as detailed in the part drawings. When this was complete, the parts were clamped together to check the fit. All joints had to fit without gaps larger than 1/16 in. to ensure quality welds. This was particularly important because the accuracy and strength of the welds were critical parts of our design in order to achieve our very low target weight. Additionally, the frame needed to be held in a fixture while it was TIG welded to ensure all members stayed straight.

The chosen thin-walled aluminum tubing for the frame provided the best strength to weight ratio that we could afford but it is very hard to weld. Our team didn't have adequate experience to complete these processes. This meant that we needed to hire an outside fabricator do this part of our building process. We found a local fabrication shop here in San Luis Obispo, CA named Gentry Welding & Fabrication. Although all other work was completed by the sit ski team, outsourcing this manufacturing step saved us a great deal of time and money while providing us with a very high quality product.

While the frame was being fabricated by Gentry, we ordered the seat and fabricated the bindings (shown in the two tracks on the right side of figure 26). The seat was ordered from Enabling Technologies, LLC. Once we received the seat, we trimmed and padded it to fit Marlon and drilled holes for mounting to the frame. Two bolts in the back and two brackets in the front secure the seat to the frame, ensuring that it is rigidly fixed.

The ski is attached with dual NNN bindings mounted on the skis in opposite directions so the ski can be connected with four pins. A steel pin was mounted in the C channel aluminum piece to connect into the binding. This created a pin joint to restrict forward/backward and upward motion of the ski and the channel that fits over the binding restricts side to side motion. The bindings were fabricated separate from the frame and attached after the frame was complete. This allowed for simultaneous manufacturing and reduced our overall build time.

The final assembly process will included adding straps, and a foot rest. The straps are nylon webbing with foam wherever there could be pressure points creating comfortable restraint system. The thigh straps are riveted directly to the seat. The foot rest consists of a foot plate mounted to the front of the ski's frame on which the rider's feet rest. To secure the riders feet, straps over the ankles were added to restrict any motion in the legs. These straps will also be made of nylon webbing and will be riveted to the foot plate. This whole foot plate assembly is capable of pivoting about the front tube on the frame. The top of the foot plate is connected to the seat support on the frame with a ratcheting cam strap. This allows the rider to adjust the angle of the foot plate in order to stretch their calves and stop any extensor spasms they may experience.

The complete manufacturing of the sit ski took approximately 164 hours. Each of the manufacturing processes and the estimate of the hours needed to be complete each task are tabulated in Table 5. Some of these tasks were outsourced to professionals because they involved challenging processes that were beyond the expertise of our team.

Table 5. Time Estimates for Fabrication.

Task	**Time (hrs)**
Cut & Miter Tubes (CPSS)	30
Bend Tubes (Professional)	2
Fixture Frame (Gentry Fabrication, SLO)	20
Weld Frame (Gentry Fabrication, SLO)	6
Drill Frame (CPSS)	4
Finalize Seat Mold (CPSS)	8
Layup Carbon & Cure (CPSS)	20
Trim & Drill Seat (CPSS)	8
Install Padding (CPSS)	8
Machine & Drill U Channel (CPSS)	12
Press in Binding Pins & Hardened Sleeves (CPSS)	6
Fabricate Restraints & Footrest (CPSS)	20
Mount Bindings on Skis (CPSS)	5
Assemble Bindings, Frame, & Seat (CPSS)	15
Total (CPSS)	136
Total (Gentry Fabrication, SLO)	28
Total	164

6.2 Manufacturing Resources Used

The fabrication of the sit ski will involve several processes and several types of processes. The manufacturing resources needed to fabricate the sit ski include:

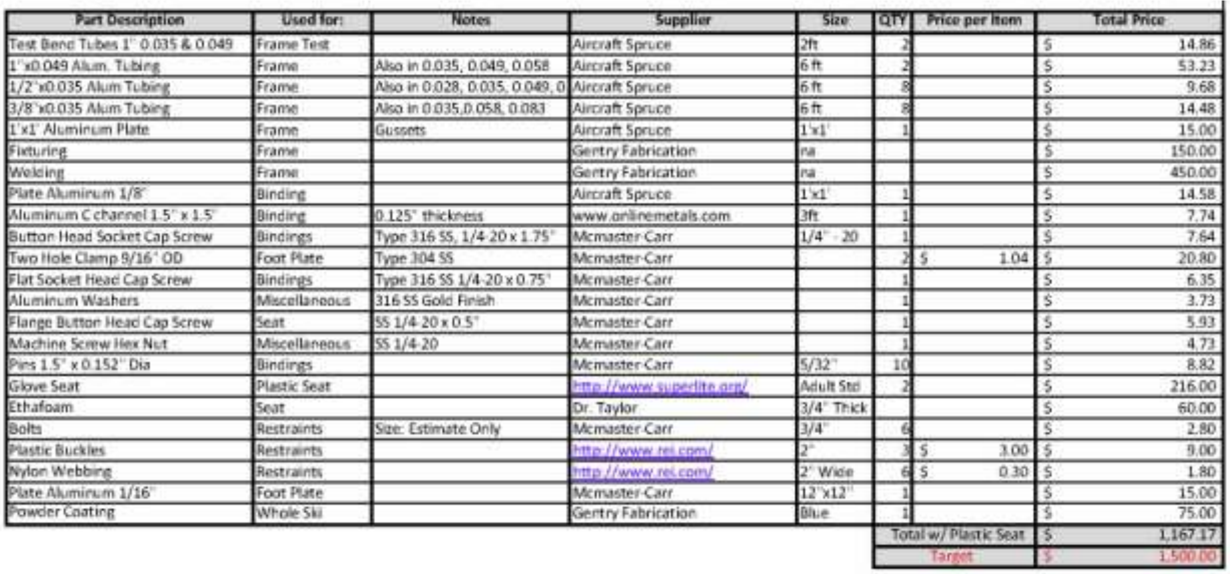
TIG welding with fixture
Large rivet gun
Vertical axis mill
Drill press
Vertical and horizontal band saws
Metal sanders

All of these resources were either readily available in the Cal Poly Mechanical Engineering Department laboratories or were outsourced to Gentry Welding & Fabrication in San Luis Obispo, CA.

6.3 Procurement & Cost Analysis

The materials for the sit ski were purchased from several different suppliers both locally and from internet sources. A material and supplier list is shown in Table 6 below.

Table 6. Preliminary Materials List with Suppliers and Pricing



Part Description	Used for:	Notes	Supplier	Size	QTY	Price per Item	Total Price
Test Bend Tubes 1'' 0.035 & 0.049	Frame Test		Aircraft Spruce	2ft	2		$ 14.86
1''x0.049 Alum. Tubing	Frame	Also in 0.035, 0.049, 0.058	Aircraft Spruce	6 ft	2		$ 53.23
1/2''x0.035 Alum Tubing	Frame	Also in 0.028, 0.035, 0.049, 0	Aircraft Spruce	6 ft	8		$ 9.68
3/8''x0.035 Alum Tubing	Frame	Also in 0.035,0.058, 0.083	Aircraft Spruce	6 ft	8		$ 14.48
1'x1' Aluminum Plate	Frame	Gussets	Aircraft Spruce	1'x1'	1		$ 15.00
Fixturing	Frame		Gentry Fabrication	na			$ 150.00
Welding	Frame		Gentry Fabrication	na			$ 450.00
Plate Aluminum 1/8''	Binding		Aircraft Spruce	1'x1'	1		$ 14.58
Aluminum C channel 1.5'' x 1.5''	Binding	0.125'' thickness	www.onlinemetals.com	3ft	1		$ 7.74
Button Head Socket Cap Screw	Bindings	Type 316 SS, 1/4-20 x 1.75''	Mcmaster-Carr	1/4'' - 20	1		$ 7.64
Two Hole Clamp 9/16'' OD	Foot Plate	Type 304 SS	Mcmaster-Carr		2	$ 1.04	$ 20.80
Flat Socket Head Cap Screw	Bindings	Type 316 SS 1/4-20 x 0.75''	Mcmaster-Carr		1		$ 6.35
Aluminum Washers	Miscellaneous	316 SS Gold Finish	Mcmaster-Carr		1		$ 3.73
Flange Button Head Cap Screw	Seat	SS 1/4-20 x 0.5''	Mcmaster-Carr		1		$ 5.93
Machine Screw Hex Nut	Miscellaneous	SS 1/4-20	Mcmaster-Carr		1		$ 4.73
Pins 1.5'' x 0.152'' Dia	Bindings		Mcmaster-Carr	5/32''	10		$ 8.82
Glove Seat	Plastic Seat		http://www.superlite.org/	Adult Std	2		$ 216.00
Ethafoam	Seat		Dr. Taylor	3/4'' Thick			$ 60.00
Bolts	Restraints	Size: Estimate Only	Mcmaster-Carr	3/4''	6		$ 2.80
Plastic Buckles	Restraints		http://www.rei.com/	2''	3	$ 3.00	$ 9.00
Nylon Webbing	Restraints		http://www.rei.com/	2'' Wide	6	$ 0.30	$ 1.80
Plate Aluminum 1/16''	Foot Plate		Mcmaster-Carr	12''x12''	1		$ 15.00
Powder Coating	Whole Ski		Gentry Fabrication	Blue	1		$ 75.00
					Total w/ Plastic Seat		$ 1,167.17
					Target		$ 1,500.00

6.4 Manufacturing Flow Diagram

To reduce the time required for manufacturing, processes must be competed simultaneously. This process is outlined in the manufacturing flow diagram shown in Figure 27 below.

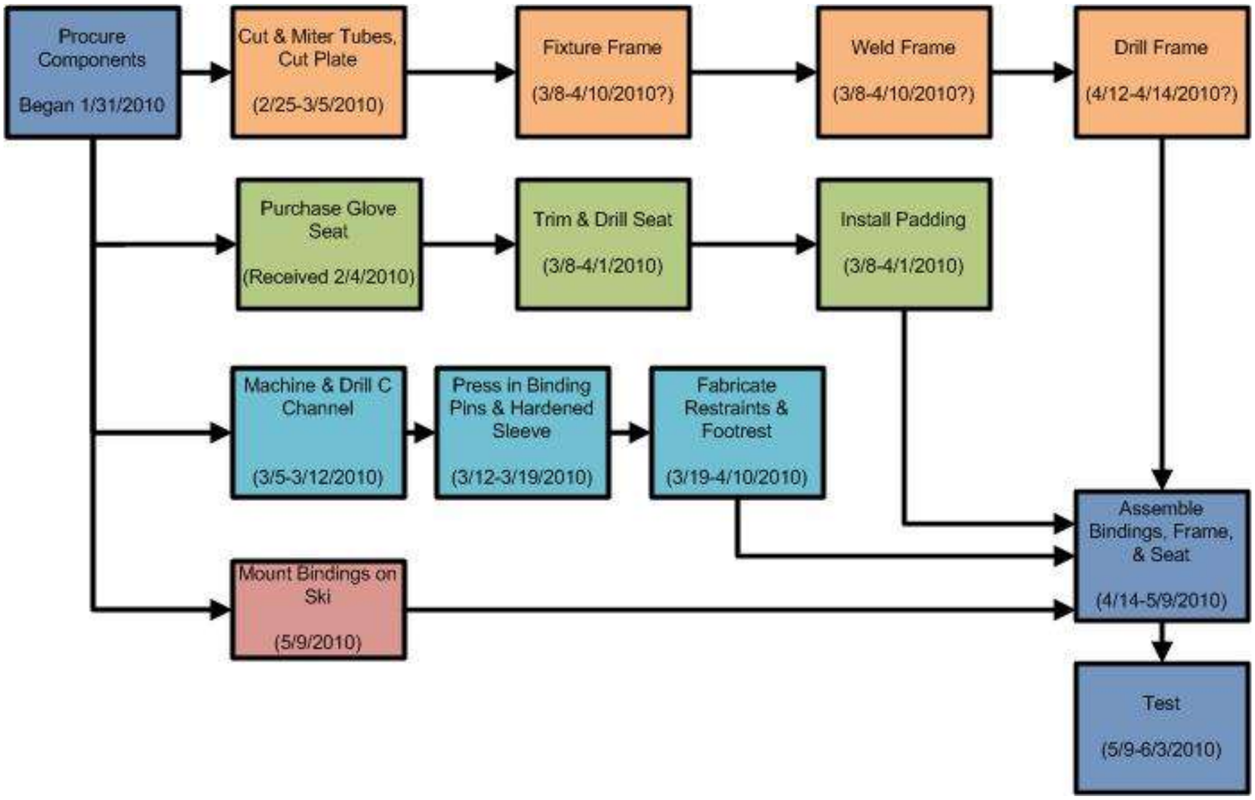


Figure 27. Manufacturing flow diagram showing simultaneous fabrication. The tan box on the top row with the red border shows the step for the welding of the frame that we will need to contract out. All other manufacturing will be completed by the Cal Poly Sit Ski team.

6.5 Safety

Safety is an important consideration for any design. It is our responsibility to make sure that the design is as safe as possible. Proper analysis and testing will be completed in order to ensure that no part of the design fails during regular use. However, additional special considerations are needed because people with spinal cord injuries may not be able to feel their lower body and we must make sure that the design has no pressure points or sharp edges that might cause sores on the athlete as they ski. Even a small pressure point can cause a large health problem if it is not found before it creates an open sore. The decreased healing capacity of people with spinal cord injuries slows the healing of open wounds and makes them more susceptible to infection.

Another design consideration is the restraint system required to hold the athlete in the ski. This system must hold the athlete securely without impacting circulation or causing pressure points. It must also be able to withstand motion from spasticity in the lower limbs of athletes without coming lose or rubbing.

Another consideration would be making sure that the geometry of the ski is such that the athlete can right himself or herself after a crash. This may mean keeping the seat height low enough that Mr. Shepard can touch the ground with his hands while he is seated upright in the ski.

Because this is the first prototype of an experimental design where weight must be optimized, low safety factors were used. This allowed the use of very thin tubing on the frame. During testing the tubing was found to be prone to bending under sudden loading. More details on this response can be found in the Design Verification section.

6.6 Drawings

A full set of manufacturing, layout, and part drawings for this design are attached in Appendix C. The top level assembly is drawing number 1000. The first subassembly is the Frame; it has Drawing numbers in the 1100 series. The second subassembly is the Seat with 1200 series drawing numbers. The third and last subassembly is the Binding, the 1300 series. These assemblies each have individual components that are consecutively ordered from the initial assembly, 1101, 1102, etc.

7. Design Verification

To test the design and verify that all of the design specifications were satisfied, we used failure mode and effects analysis (FMEA) and a formalized design verification plan and report (DVP&R).

7.1 Failure Modes and Effects Analysis

The failure mode and effects analysis, or FMEA as it is commonly referred to, was used as a way to consider potential ways that the sit ski may fail or break. The FMEA points out places in a design where failure could occur that may not have been considered in the design process. The implementation of this analysis has led to a better design since we thought about what could have gone wrong before anything did. Thus the FMEA was used to design against failure. The FMEA is shown in Appendix E.

A FMEA starts by listing the main elements or functions of the product in the left hand column of a matrix. The next column listed potential ways that each function of the sit ski could fail. Then we listed how each element could fail and what the effects of each failure could be. Potential causes of the failure are then listed, along with the severity of failure and the occurrence. The severity is rated on a 1-10 scale from the user's perspective, with 1 being the lowest. The occurrence is also on a 1-10 scale with 1 being the lowest.

Next, a detection ranking was assigned to each row, also on a 1-10 scale, where a 10 is undetectable and 1 is easily detectable. The occurrence, detection and severity are multiplied together to give each potential failure a "priority ranking," so that high risk failures can be seen. Lastly, recommended actions to prevent each failure are listed, along with an action taken column that is used to show how failure modes have been decreased or prevented. It is important to note that the FMEA was used throughout the course of product design and development since new potential failures could have arose.

7.2 Design Verification and Report

The design verification and report (DVP&R) is divided into two sections: the plan section and the report section. The plan portion of the DVP&R outlines the testing that was required to verify our design and the report portion documents the results of the tests. The DVP&R picks up where the FMEA leaves off. While the FMEA tells us how and where the design could possibly fail, the DVP&R outlines the tests that are needed to make sure that it will not fail in any of these modes. In addition, the DVP&R documents the test results so that we do not repeat any mistakes or conduct unnecessary tests.

7.3.1 Test Plan

The DVP&R leads us right into our test plan. The testing of the sit ski was conducted from May 15th to June 2nd. The tests were broken up into three main categories based on their subjectivity. The objective tests were conducted first to ensure that the ski is structurally sound then we put the sit ski on roller skis and test rode it to run the more subjective tests.

Objective Tests:

1. ***Weight*** - Place the ski on a scale, record weight.
2. ***Vertical ski deflection*** - Place 80 lb vertical load on ski at the bindings on one side, fix the other side and measure the linear vertical deflection in the ski.
3. ***Horizontal ski roll*** - Place 60 lb horizontal load on ski at the binding on one side, fix the other side and measure the linear horizontal deflection in the ski.
4. ***Angular ski deflection*** - Place 5 lbs horizontal load on ski tip on one ski, fix the frame and measure the angular deflection in the ski centerline.
5. ***Angular ski roll*** - Place small torque (5 ft-lbs) on the ski, fix the frame and measure angular deflection in the ski.
6. ***Time to remove skis*** - Use a stopwatch to time the removal of the skis.
7. ***Time to attach self to ski*** - Use a stopwatch to time how long it takes athlete to attach himself.
8. ***Deflection of the foot rest*** - Place 30 lb vertical load on foot rest, fix the bindings and measure the linear deflection in the foot rest.
9. ***Restraints strength*** - Hold the frame and seat steady. Place 50 lb load on closed restraint. Check for failure.

Possibly Subjective Tests:

1. ***Number of sharp edges*** - Feel for any sharp edges that could contact the rider during skiing
2. ***Number of pressure points*** - Feel for any pressure points or sources of rubbing while riding the ski.

Subjective Tests:

1. ***Restraints*** – Check that the restraints hold the rider securely and do not rub during use.
2. ***Stability*** - Ride ski to test for tipping during turning and skiing
3. ***Ability to right yourself*** - Strap athlete to the ski, lay them on their side and allow them to push themselves back upright
4. ***Seat comfort*** - Road test with roller skis

The required equipment for all these tests includes: a scale, clamps, a sturdy table to clamp the sit ski to, two skis to mount the sit ski onto, a ruler, a stopwatch, various weights up to 60lbs, a rider, and a protractor.

7.3.2 Test Results

7.3.2.1 Objective Test Results

The objective tests were performed on May 24, 2010. All but two tests were successful. The vertical ski deflection test was not performed due to the permanent deformation of the frame that would result. The 80lb load could not be applied in an isolated manner due to the lack of fixturing form the frame. Because of this, we do not have results for the vertical ski deflection test but based on our judgment, we feel the ski is adequate in this area. Additionally, the frame failed the angular ski roll test by one degree. Although this was above the specification that was originally set, it appears to still be acceptable. The results of the tests are shown below in Table 27. Pictures of the testing are also shown below in Figure 28.

Table 27. Subjective tests and the results from each. Details for each test can be found in the DVP&R

Specification or Clause Reference	Acceptance Criteria	TEST RESULTS
		Test Result
Weight	< 10 lbs	Pass 8 lbs
Vertical ski deflection	< .5 in	Not Performed
Horizontal ski deflection	< .5 in	Pass 0.25 in
Angular ski deflection	< 5 deg	Pass 0.2 deg
Angular ski roll	< 3 deg	Pass 3 deg
Time to remove skis	< 1 min	Pass 15 sec
Time to attach self to ski	< 2 min	Pass 30 sec
Deflection of foot rest	< .25 in	Pass 3/16 in
Restraints	No failure	Pass

Figure 28A. Deflection of footrest test.

Figure 28B. Angular Ski roll test.

Figure 18C. Horizontal ski deflection test.

7.3.2.2 Possibly Subjective Test Results

The possibly subjective tests were performed on May 24, 2010. The sit ski passed both tests. The results of the tests are shown below in Table 28.

Table 28. Possibly Subjective tests and the results from each.
Details for each test can be found in the DVP&R.

Specification or Clause Reference	Acceptance Criteria	TEST RESULTS
		Test Result
Number of sharp edges	0 edges	Pass
Number of pressure points or hot spots	0 edges	Pass

7.3.2.3 Subjective Test Results

The subjective tests were performed on May 18 and 24, 2010. The most significant failure that occurred during the subjective tests was the stability test. While mounted on roller skis, the ski was ridden on a flat concrete surface. During this test, a side load was applied during a turn that caused the front right leg assembly to bend and permanently deform. The cause and results are further discussed in the test reflection below. The results of the tests are shown below in Table 29. Pictures of each test are also shown below in Figure 29.

Table 29. Subjective tests and the results from each.
Details for each test can be found in the DVP&R.

Specification or Clause Reference	Acceptance Criteria	TEST RESULTS
		Test Result
Restraints	Rider approval	Pass
Stability	Rider approval	Pass
Ability to right yourself	Rider approval	Pass
Seat comfort	Rider approval	Pass

Figure 29. Stability and rider comfort testing.

7.3.3 Test Reflection

Based on the test results, it appears this sit ski design was effective and successful. Although it did bend and fail during three of the tests, neither of these was catastrophic. The ski was not meant to undergo such strong side loads and was not designed for such dynamic turning loads with roller skis. Although it did bend, we believe once it is repaired and reinforced, the strength and stiffness of the frame will be adequate. The angular ski roll of three degrees instead of two is still manageable and should not negatively affect the ski. Even without performing the vertical ski deflection test, we believe the frame is adequately stiff.

The tests were helpful in determining how this product would react under various conditions. If it had been an option, it would have been very helpful to ride the sit ski in the snow. This would have given us a better idea of how the ski responded to the actual design conditions.

8. Management Plan

The management plan is a key component to ensuring the project stays on task and delivers a final product that meets the client's needs. To aid in the management process we have created a detailed schedule that defines project milestones. The key milestones along the project include the following:

Project Proposal	19 October 2009
Concept Design Report	11 November 2009
Critical Design Review	14 January 2010
Final Design Report	26 January 2010
Final Hardware Demo	13 May 2010
Project Design Expo	3 June 2010

These dates gave a basic structure to the project. The Gantt chart in Appendix B shows a more detailed project timeline. It also displays the critical path to project completion and the interdependency of each task. We will use the Gantt chart to evaluate our progress throughout the design, build, and test phases of the project. The schedule will become more detailed as the project progresses and specific details of each phase are established.

Our team has also generated a list of Roles and Responsibilities (see Appendix G) to make clear how we will work together as a team and meet our goals. In addition to these tools, we also consulted with Dr. Brian Self who has been involved with several prior Cal Poly Sit Ski senior projects, and Dr. Kevin Taylor who has considerable experience with people with disabilities, specifically those with spinal injuries. Jon Kreamelmeyer has also provided a wealth of knowledge about the needs and goals of the project that have helped us create a suitable design.

We worked closely with Mr. Marlon Shepard to gather information on the current sit ski and improvements that he would like to see in the design. Mr. Shepard played a crucial role throughout all phases of the project.

8.1 Team Roles and Responsibilities

Roles and responsibilities for the team were generated to ensure an even distribution of work and help each individual on our team focus on his components of the project. We continually evaluated the workload to ensure everyone had equal contribution to the final product. The table is shown in Appendix G.

9. Conclusions & Recommendations

We hope that this final report clearly defines our design and realized solution to the project. There are a few considerations that should be taken into account if another prototype sit ski is to be developed. The loading conditions used in our design proved to be inadequate in simulating the high loads generated during side loads on the ski. A dynamic sideways motion generates more load than anticipated in our analysis. Additionally, thicker tubes should be used. Through testing, the 0.035 in wall thickness tubing was proven to be inadequate and was prone to bending. The main frame was built out of 0.065 in wall thickness tubing proved to be quite strong. The next prototype should have thicker walled tubing for the frame and cut weight by only using foam where necessary on the seat.

At the athlete's request, the entire seat was covered with closed cell foam. Although this makes for a very comfortable seat with very little chance for rubbing, it added a considerable amount of weight to the ski. To reduce weight, holes could be cut in the foam where it is not necessary to have padding.

The molded plastic seat from Enabling Technologies was successful and proved to be a durable, comfortable, and relatively lightweight solution to the seat. Because the plastic can be easily cut to shape, a custom seat is easy to attain. If additional weight savings were desired, holes could be cut in the seat as long as it didn't compromise strength or stiffness.

The foot rest design could also be improved to increase the stretching force it applies to the riders calves. This could be achieved with stronger straps that don't have as much stretch.

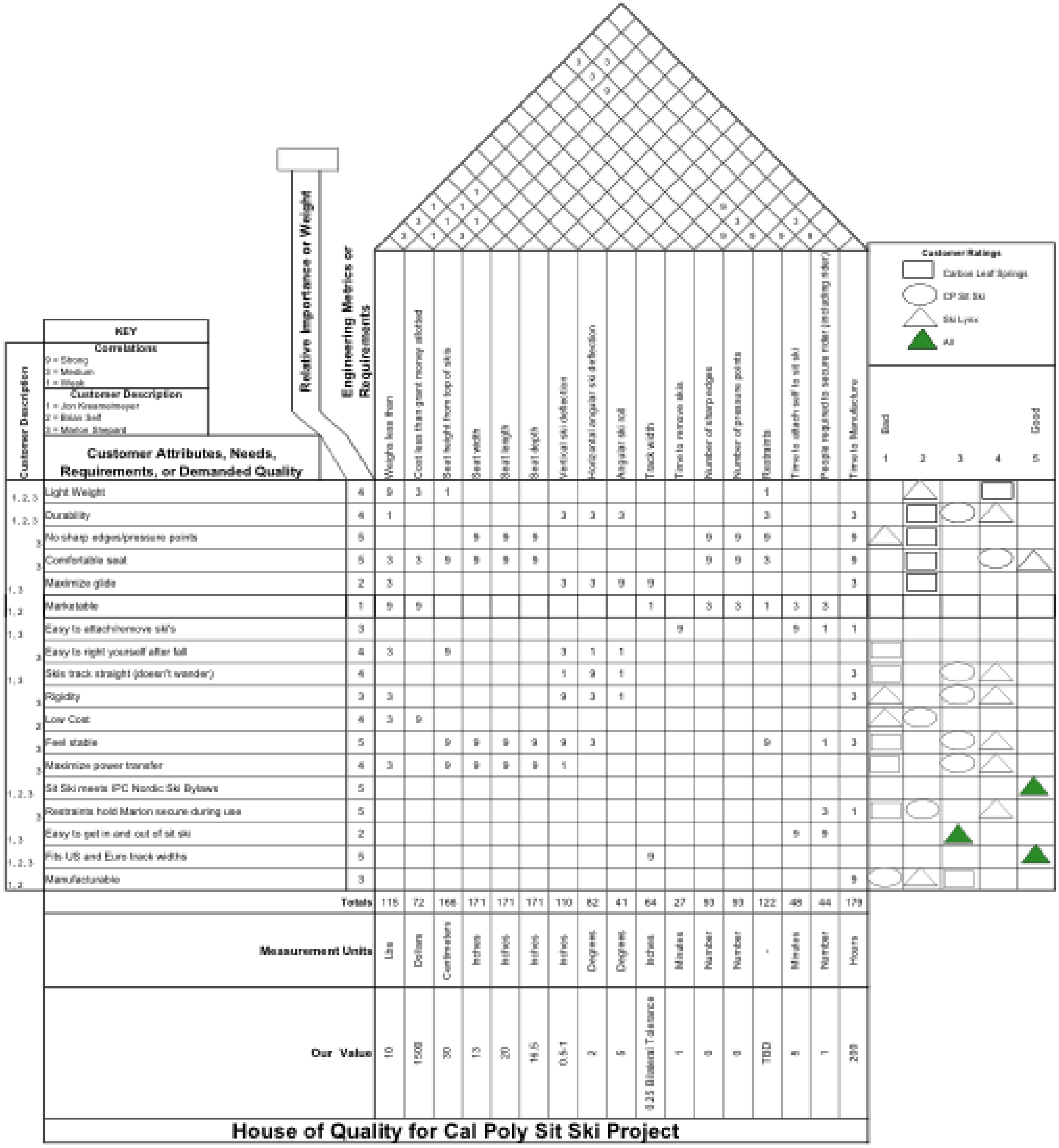
If these ideas were applied to a second prototype, the design could be significantly improved. Our project was successful in achieving an extremely lightweight design but a second prototype could allow for improved durability and better weight savings in the seat and padding.

10. Appendices

Appendix A – Quality Function Deployment (QFD)
Appendix B – Schedule (Gantt Chart)
Appendix C – Drawings
Appendix D – Analysis Hand Calculations
Appendix E – Design Failure Mode and Effects Analysis (FMEA)
Appendix F – Design Verification Plan and Report (DVP&R)
Appendix G – Roles and Responsibilities
Appendix H– References

Appendix A

Quality Function Deployment



KEY

Correlations
9 = Strong
3 = Medium
1 = Weak

Customer Description
1 = Jon Kreamelmeyer
2 = Brian Self
3 = Marion Shepard

Customer Ratings
▭ Carbon Leaf Springs
⬭ CP Sit Ski
△ Ski Lynx
▲ All

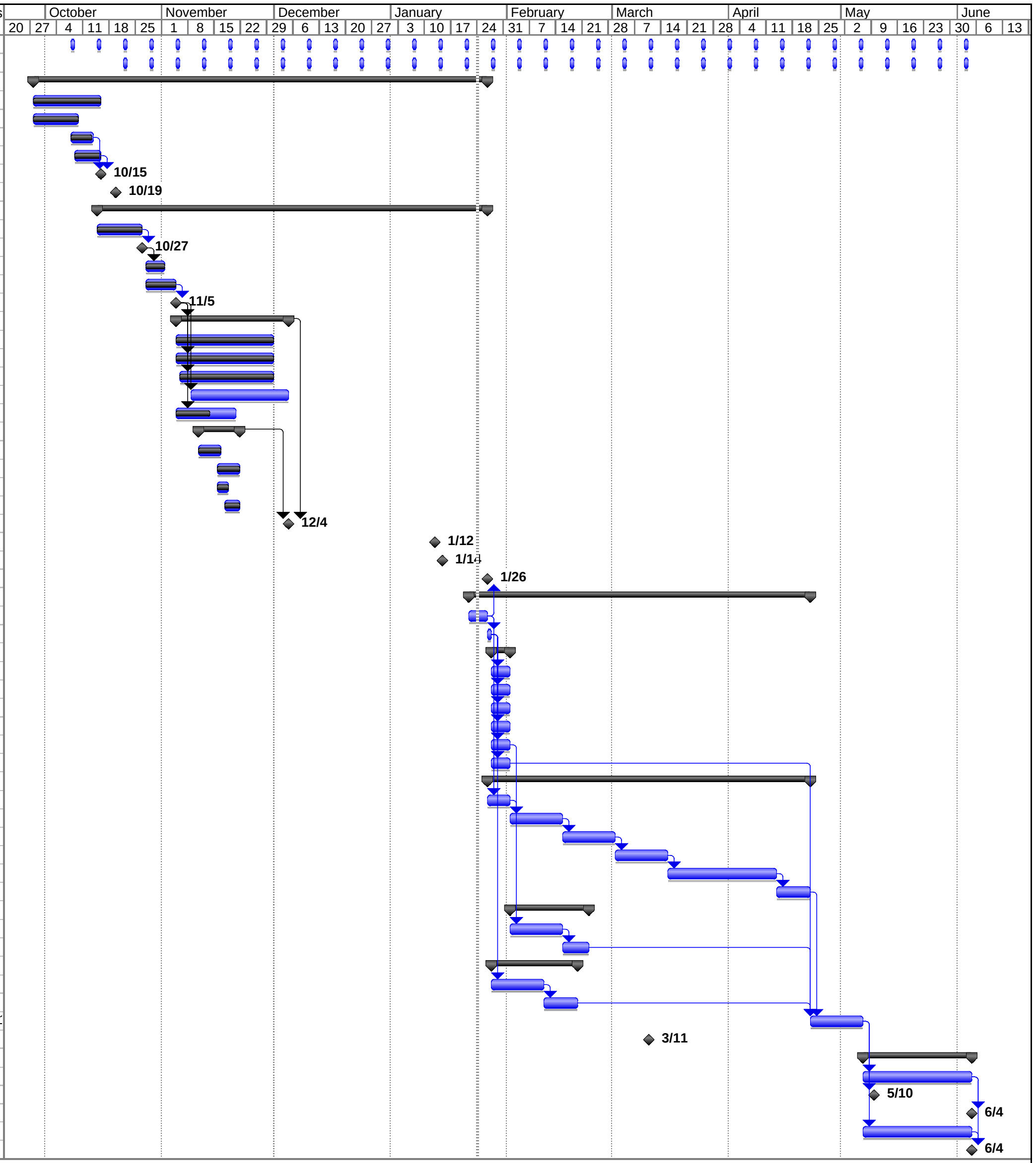
Customer Description	Customer Attributes, Needs, Requirements, or Demanded Quality	Relative Importance or Weight	Weight less than	Cost less than grant money allotted	Seat height from top of skis	Seat width	Seat length	Seat depth	Vertical ski deflection	Horizontal angular ski deflection	Angular ski roll	Track width	Time to remove skis	Number of sharp edges	Number of pressure points	Restraints	Time to attach self to sit ski	People required to secure rider (including rider)	Time to Manufacture	Bad 1	2	3	4	Good 5
1, 2, 3	Light Weight	4	9	3	1											1					△		▭	
1, 2, 3	Durability	4	1						3	3	3					3			3		▭	⬭	△	
3	No sharp edges/pressure points	5				9	9	9						9	9	9			9	△	▭			
3	Comfortable seat	5	3	3	9	9	9	9						9	9	3			9		▭		⬭	△
1, 3	Maximize glide	2	3						3	3	9	9							3		▭			
1, 2	Marketable	1	9	9								1		3	3	1	3	3						
1, 3	Easy to attach/remove ski's	3											9				9	1	1					
3	Easy to right yourself after fall	4	3		9				3	1	1									▭				
1, 3	Skis track straight (doesn't wander)	4							1	9	1								3	▭		⬭	△	
3	Rigidity	3	3						9	3	1								3	△		⬭	△	
2	Low Cost	4	3	9																△	⬭			
3	Feel stable	5			9	9	9	9	9	3						9		1	3	▭		⬭	△	
3	Maximize power transfer	4	3		9	9	9	9	1											▭		⬭	△	
1, 2, 3	Sit Ski meets IPC Nordic Ski Bylaws	5																						▲
3	Restraints hold Marion secure during use	5																3	1	▭	⬭		△	
1, 3	Easy to get in and out of sit ski	2															9	9				▲		
1, 2, 3	Fits US and Euro track widths	5										9												▲
1, 3	Manufacturable	3																	9	⬭	△	▭		
		Totals	115	72	168	171	171	171	110	82	41	64	27	93	93	122	48	44	179					
		Measurement Units	Lbs	Dollars	Centimeters	Inches	Inches	Inches	Inches	Degrees	Degrees	Inches	Minutes	Number	Number	-	Minutes	Number	Hours					
		Our Value	10	1500	30	13	20	16.5	0.5-1	2	5	0.25 Bilateral Tolerance	1	0	0	TBD	5	1	288					

House of Quality for Cal Poly Sit Ski Project

Appendix B

Schedule

ID	ℹ	Task Name	Duration	Start	Finish	Notes	Predecess
1	⟳	**Meet with Sarah Harding**	**172 days**	**Thu 10/8/09**	**Thu 6/3/10**		
37	⟳	**Meet with Theresa Field**	**162 days**	**Thu 10/22/09**	**Thu 6/3/10**		
71		**Design Phase**	**88 days?**	**Mon 9/28/09**	**Tue 1/26/10**		
72	✓ 📝	Background Research	14 days?	Mon 9/28/09	Thu 10/15/09	e quarter.	
73	✓	Problem Description	10 days	Mon 9/28/09	Fri 10/9/09		
74	▦ 📝	QFD Specifications	4 days?	Thu 10/8/09	Tue 10/13/09	r project.	
75	✓	Write Project Proposal	5 days?	Fri 10/9/09	Thu 10/15/09		
76	✓	Project Proposal	0 days	Thu 10/15/09	Thu 10/15/09		75,74
77	▦ 📝	Detailed Schedule Due	0 days	Mon 10/19/09	Mon 10/19/09	ate Done.	
78		**Concept Design**	**75 days?**	**Thu 10/15/09**	**Tue 1/26/10**		
79	✓	Brainstorming & Concept Generation	8 days?	Thu 10/15/09	Mon 10/26/09		
80	✓	Concept Design Review	0 days	Tue 10/27/09	Tue 10/27/09		79
81	✓	Refine Concepts	4 days?	Wed 10/28/09	Sun 11/1/09		80
82	✓	Write Concept Report	7 days	Wed 10/28/09	Wed 11/4/09		
83	▦	Concept Report Due	0 days	Thu 11/5/09	Thu 11/5/09		82
84		**Work on Draft Design Report**	**22 days?**	**Thu 11/5/09**	**Fri 12/4/09**		**83**
85	✓	Composite Fiber Research	18 days?	Thu 11/5/09	Mon 11/30/09		
86	✓	Material selection research	18 days?	Thu 11/5/09	Mon 11/30/09		83
87	✓	Work on getting a mold of Marlon	17 days?	Fri 11/6/09	Mon 11/30/09		83
88	▦	Build Tracksetter/ Get yellow tag	20 days?	Mon 11/9/09	Fri 12/4/09		83
89		Supplier research	12 days?	Thu 11/5/09	Fri 11/20/09		83
90	✓	**Analysis**	**8 days?**	**Wed 11/11/09**	**Sat 11/21/09**		
91	✓	Force Analysis	4 days?	Wed 11/11/09	Mon 11/16/09		
92	✓	Size Tubing	5 days?	Mon 11/16/09	Sat 11/21/09		
93	✓	Deflection Analysis	3 days?	Mon 11/16/09	Wed 11/18/09		
94	✓	Fatigue Analysis	3 days?	Wed 11/18/09	Sat 11/21/09		
95	▦	428 Draft Design Report Due	0 days	Fri 12/4/09	Fri 12/4/09		90,84
96	▦	Critical Design Review Presentations	0 days	Tue 1/12/10	Tue 1/12/10		
97	▦	Critical Design Review with Sponsor	0 days	Thu 1/14/10	Thu 1/14/10		
98	▦	Final Design Report	0 days	Tue 1/26/10	Tue 1/26/10		100
99		**Build Phase**	**65 days?**	**Fri 1/22/10**	**Thu 4/22/10**		
100	▦	Finalize Manufacturing Drawings	3 days	Fri 1/22/10	Tue 1/26/10		
101		Finalize BOM	1 day?	Wed 1/27/10	Wed 1/27/10		100
102		**Procurement**	**3 days**	**Thu 1/28/10**	**Mon 2/1/10**		
103		Order Aluminum Tubing	3 days	Thu 1/28/10	Mon 2/1/10		101
104		Order Glove Seat System	3 days	Thu 1/28/10	Mon 2/1/10		101
105		Order Binding C-channel and Components	3 days	Thu 1/28/10	Mon 2/1/10		101
106		Order Restraint Components	3 days	Thu 1/28/10	Mon 2/1/10		101
107		Order Bindings	3 days	Thu 1/28/10	Mon 2/1/10		101
108		Order Assembly Hardwear	3 days	Thu 1/28/10	Mon 2/1/10		101
109		**Frame**	**62 days**	**Wed 1/27/10**	**Thu 4/22/10**		
110	▦	Contact Gentry Fabrication	4 days	Wed 1/27/10	Mon 2/1/10		100
111		Cut & Miter Tubes	10 days	Tue 2/2/10	Mon 2/15/10		110
112		Bend Tubes	10 days	Tue 2/16/10	Mon 3/1/10		111
113		Fixture Frame	10 days	Tue 3/2/10	Mon 3/15/10		112
114		Weld Frame	21 days	Tue 3/16/10	Tue 4/13/10		113
115		Age Harden Frame	7 days	Wed 4/14/10	Thu 4/22/10		114
116		**Bindings**	**15 days**	**Tue 2/2/10**	**Mon 2/22/10**		
117		CNC Machining	10 days	Tue 2/2/10	Mon 2/15/10		107
118		Mount Pin	5 days	Tue 2/16/10	Mon 2/22/10		117
119		**Seat**	**17 days**	**Thu 1/28/10**	**Fri 2/19/10**		
120		Purchase Seat	10 days	Thu 1/28/10	Wed 2/10/10		101
121		Pad Seat	7 days	Thu 2/11/10	Fri 2/19/10		120
122		Final Assembly	10 days	Fri 4/23/10	Thu 5/6/10		121,118,1
123	▦	Project Update Report	0 days	Thu 3/11/10	Thu 3/11/10		
124		**Test Phase**	**21 days**	**Fri 5/7/10**	**Fri 6/4/10**		
125		Test Ski for Each Specification	21 days	Fri 5/7/10	Fri 6/4/10		122
126	▦	Final Hardware Demo	0 days	Mon 5/10/10	Mon 5/10/10		122
127	▦	Senior Project Design Expo	0 days	Fri 6/4/10	Fri 6/4/10		125
128		Write Report	21 days	Fri 5/7/10	Fri 6/4/10		122
129	▦	Final Project Reports Due	0 days	Fri 6/4/10	Fri 6/4/10		125,128



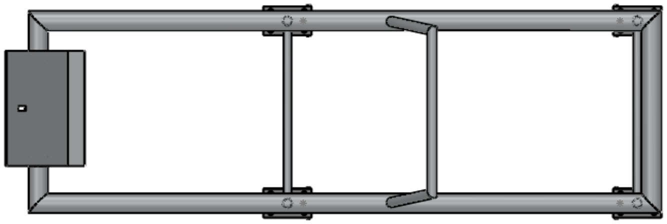
Project: Gantt Chart 1-23-10
Date: Sun 1/24/10

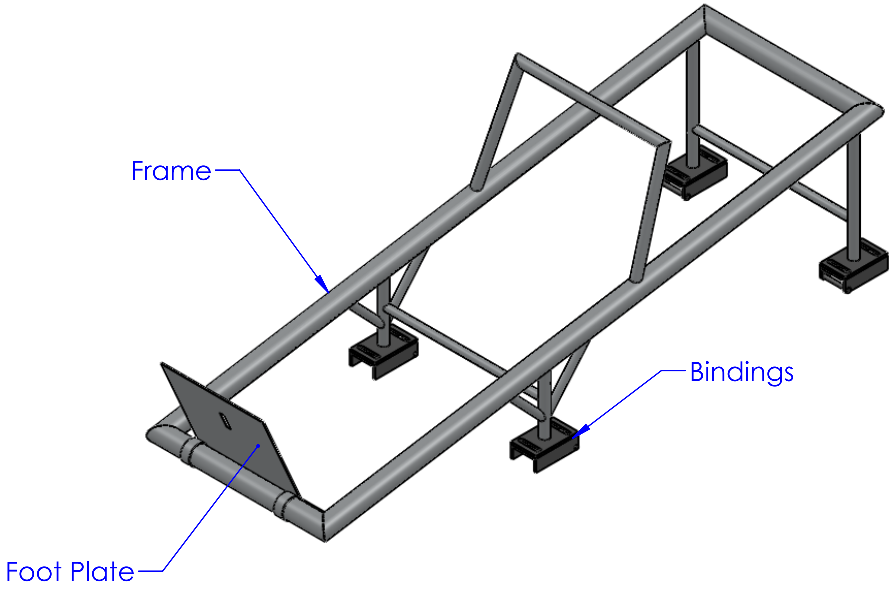
Task	▬	Progress	▬	Summary	▬	External Tasks	▬	Deadline	⇩
Split	┄	Milestone	◆	Project Summary	▬	External Milestone	◆		

Appendix C

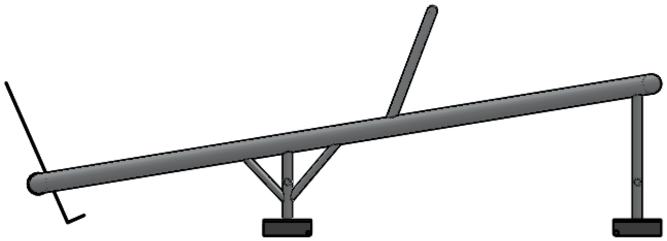
Drawings

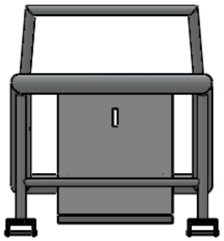
Drawings are shown on the following pages.





Note: Seat not shown

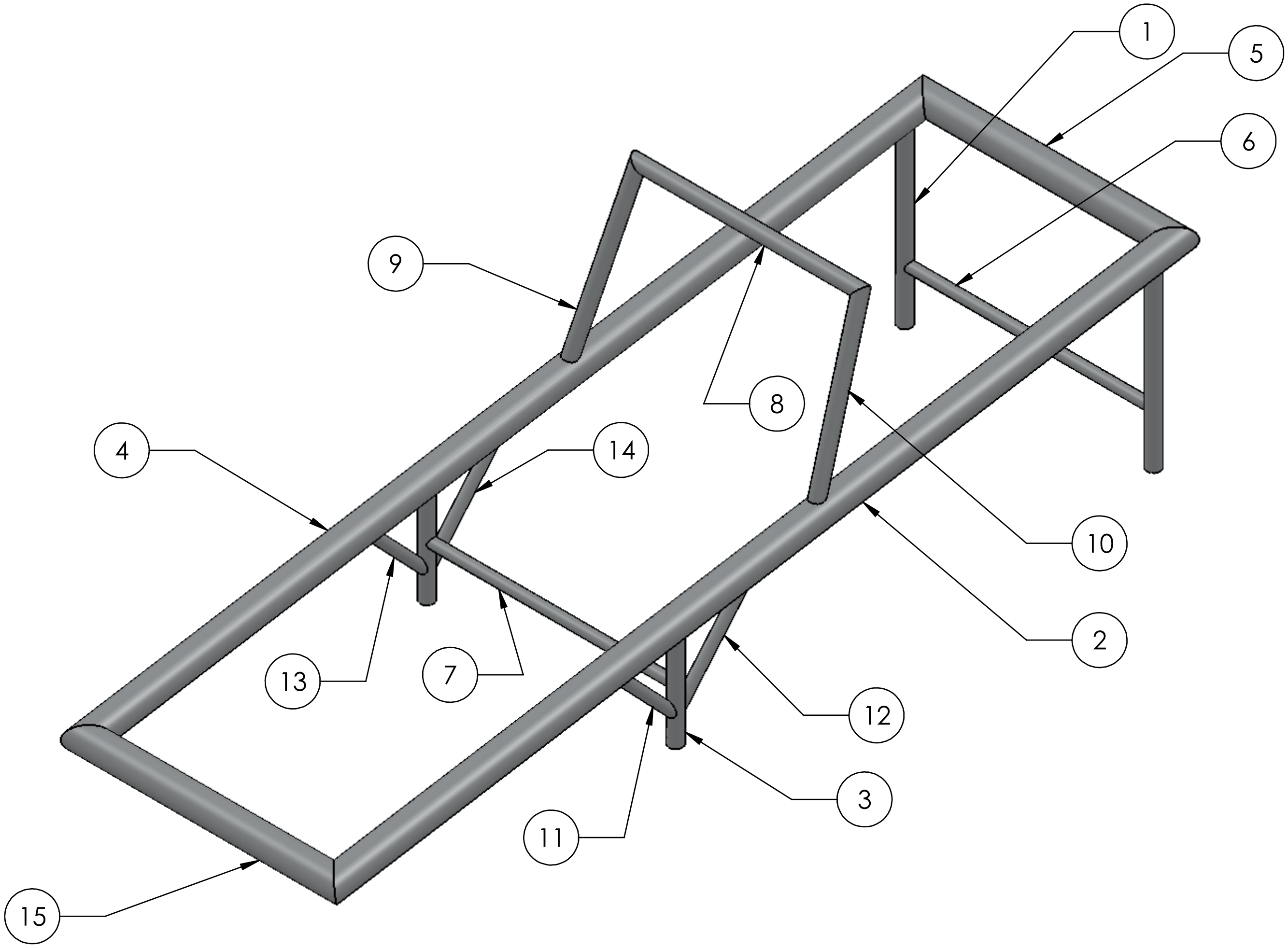




Mechanical Engineering
CAL POLY

ME428 - Fall 2009

Notes: Seat not shown		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE:	MATERIAL: 6061 T6 Aluminum
DATE: 2/8/2010	UNITS: INCHES	TITLE: Full Assembly
NEXT ASSY:	DRAWING #: 1000	GROUP:



Notes:		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE: 1:5	MATERIAL: 6061 T6 Aluminum
DATE: 2/8/2010	UNITS: INCHES	TITLE: Frame Assembly Drawing
NEXT ASSY: 1000	DRAWING #: 1100	GROUP:

Mechanical Engineering CAL POLY

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ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	LENGTH	ANGLE1	ANGLE2	MATERIAL
1	1106	Back Uprights, SCH 40, .50 DIA.	2	6.57	0	-	6061 T6 0.5" OD x 0.049" Wall
2	1101	Left Rail	1	33.42	45	45	6061 T6 1.0" OD x 0.049" Wall
3	1109	Front Uprights, SCH 40, .50 DIA.	2	3.6	0	-	6061 T6 0.5" OD x 0.035" Wall
4	1101	Right Rail	1	33.42	45	45	6061 T6 1.0" OD x 0.049" Wall
5	1102	Back Seat Support	1	10.5	45	45	6061 T6 1.0" OD x 0.049" Wall
6	1107	Back Cross Member	1	9.17	-	-	6061 T6 0.375" OD x 0.035" Wall
7	1108	Front Cross Member	1	9.17	-	-	6061 T6 0.375" OD x 0.035" Wall
8	1104	Front Seat Support	1	8.96	43	43	6061 T6 0.5" OD x 0.035" Wall
9	1103	Right Seat Support Upright	1	6.3	43	-	6061 T6 0.5" OD x 0.035" Wall
10	1105	Left Seat Support Upright	1	6.3	-	43	6061 T6 0.5" OD x 0.035" Wall
11	1113	Left Front Diagonal Support	1	2.98	-	-	6061 T6 0.375" OD x 0.035" Wall
12	1114	Left Rear Diagonal Support	1	3.9	-	-	6061 T6 0.375" OD x 0.035" Wall
13	1113	Right Front Diagonal Support	1	2.98	-	-	6061 T6 0.375" OD x 0.035" Wall
14	1114	Right Rear Diagonal Support	1	3.9	-	-	6061 T6 0.375" OD x 0.035" Wall
15	1102	Foot Support	1	10.5	-	-	6061 T6 1.0" OD x 0.049" Wall

Mechanical Engineering
CAL POLY

ME428 - Fall 2009

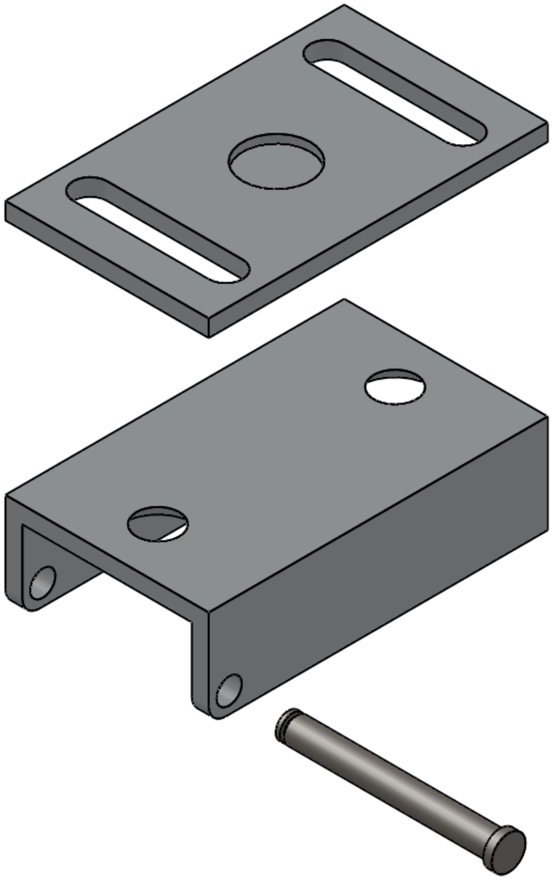
Notes:		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE: N/A	MATERIAL: 6061 T6 Aluminum
DATE: 12/2/2009	UNITS: INCHES	TITLE: Frame Assembly Drawing
NEXT ASSY: 1000	DRAWING #: 1100	GROUP:

SEAT IS TO BE VENDER SUPPLIED BY
ENABLING TECHNOLOGIES, INC
www.superlite.org

Mechanical Engineering
CAL POLY

ME428 - Fall 2009

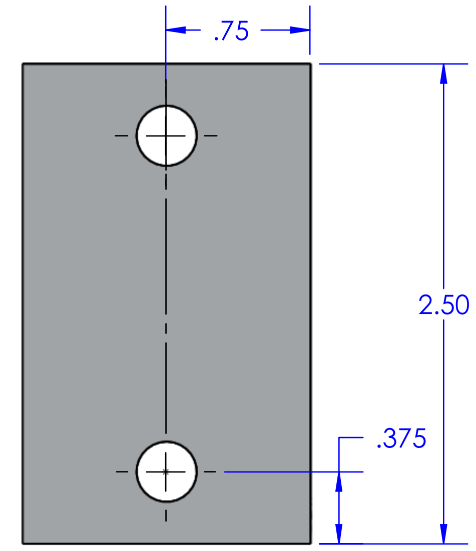
Notes:		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE:	MATERIAL: Plastic
DATE: 2/8/2010	UNITS: INCHES	TITLE: Seat Assembly
NEXT ASSY: 1000	DRAWING #: 1200	GROUP:

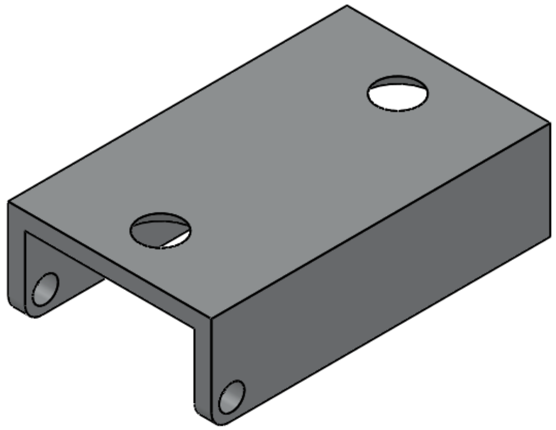


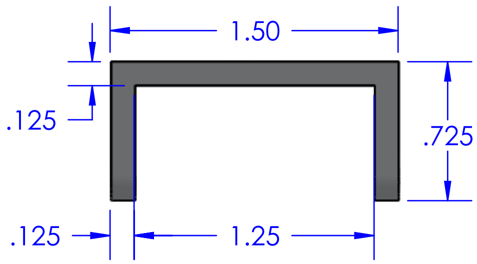
Mechanical Engineering
CAL POLY

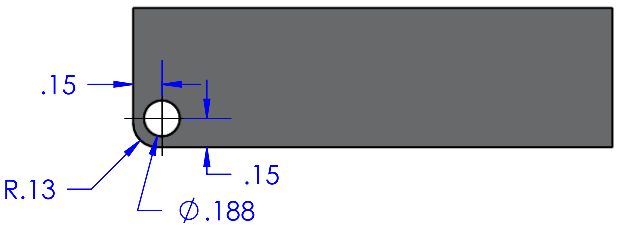
ME428 - Fall 2009

Notes: Top Plate welds to frame post		DRAWN BY: Cal Poly Sit Ski	
TOLERANCE:	SCALE: 1:1	MATERIAL: 6061 T6 Aluminum	
DATE: 2/1/10	UNITS: INCHES	TITLE: Binding Assembly	
NEXT ASSY: 1000	DRAWING #: 1300	GROUP: Binding	





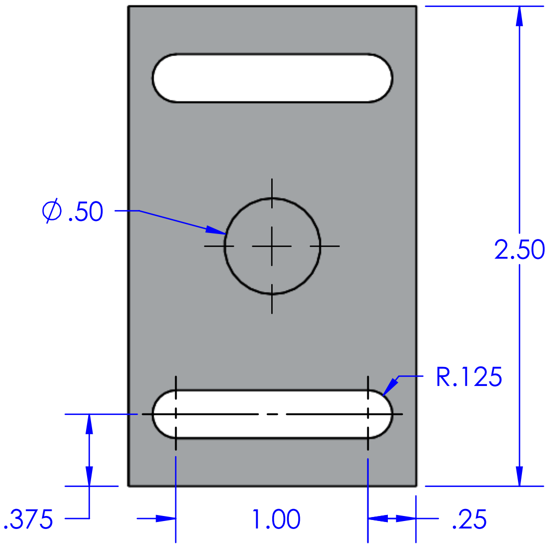


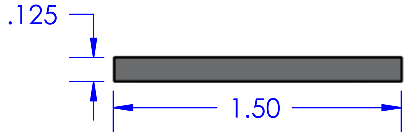


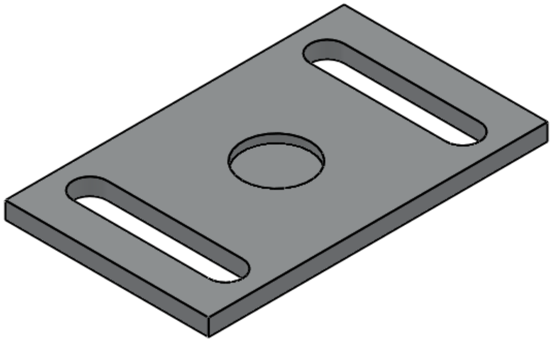
Mechanical Engineering
CAL POLY

ME428 - Fall 2009

Notes: Machined from C-channel Aluminum		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE: 1:1	MATERIAL: 6061 T6 Aluminum
2/1/10	UNITS: INCHES	TITLE: Binding
NEXT ASSY: 1300	DRAWING #: 1301	GROUP: Binding



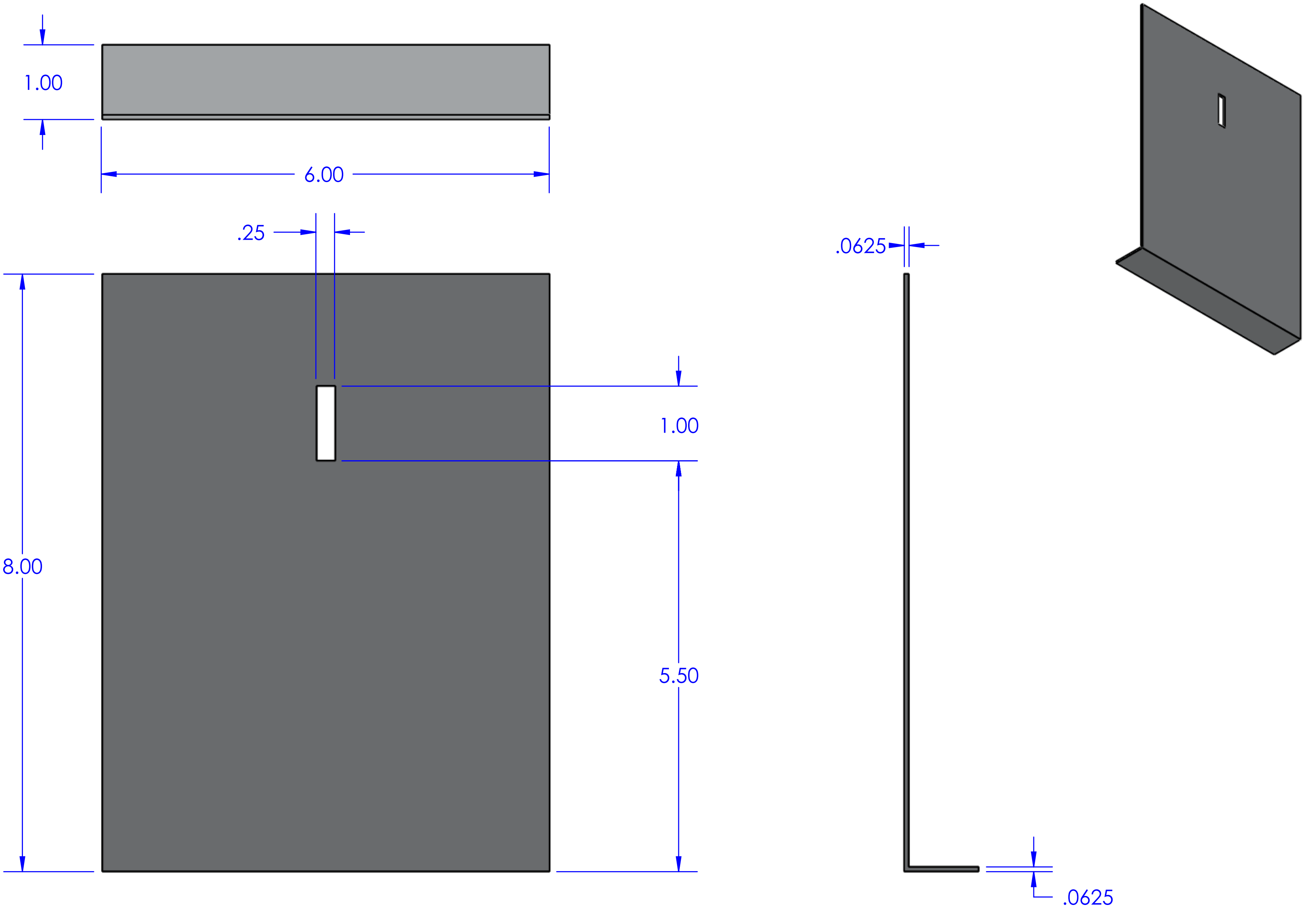




Mechanical Engineering
CAL POLY

ME428 - Fall 2009

Notes: Machined from 1/8 in plate		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE: 1:1	MATERIAL: 6061 T6 Aluminum
DATE: 2/1/10	UNITS: INCHES	TITLE: Binding Top Plate
NEXT ASSY: 1300	DRAWING #: 1302	GROUP: Binding



Mechanical Engineering
CAL POLY

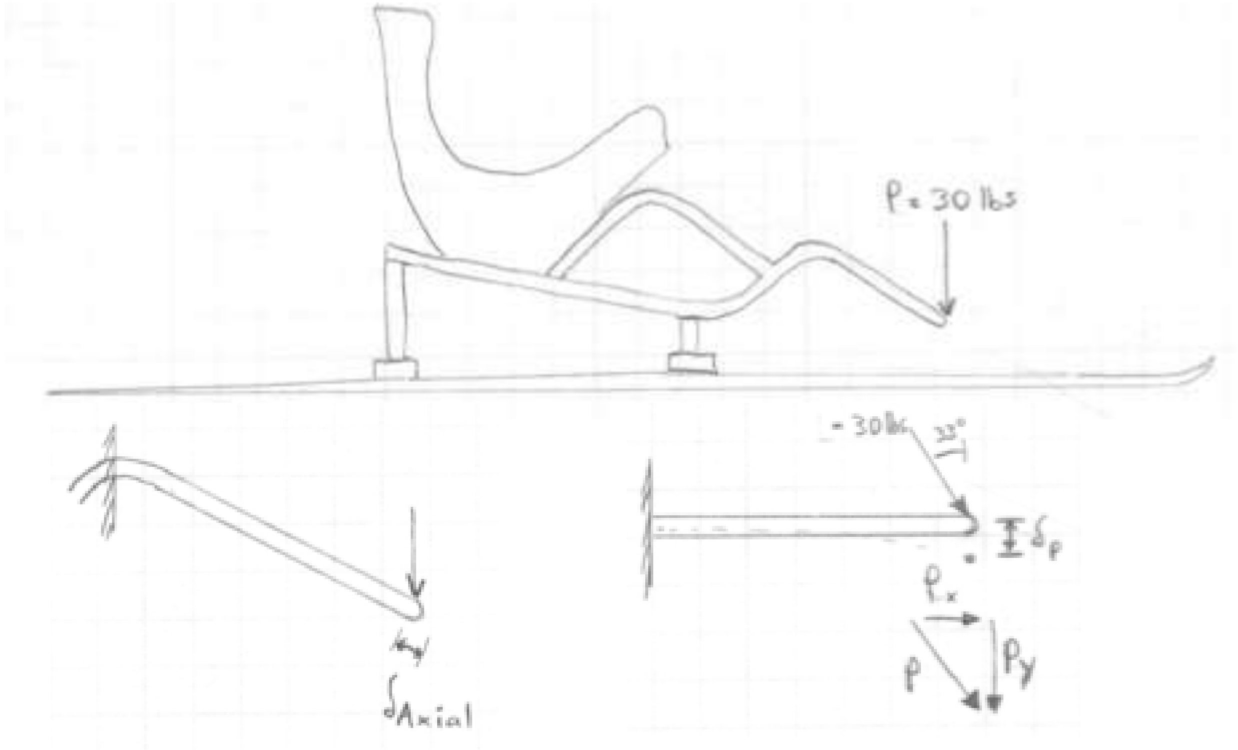
ME428 - Fall 2009

Notes:		DRAWN BY: Cal Poly Sit Ski
TOLERANCE:	SCALE:	MATERIAL: 6061 T6 Aluminum
DATE: 2/8/2010	UNITS: INCHES	TITLE: Foot Plate
NEXT ASSY: 1000	DRAWING #: 1400	GROUP:

Appendix D

Hand Calculations

1. **Deflection of footrest:**
   Modeled the footrest as a cantilever beam with one end fixed.



$$P = 30\ lbs$$
$$P_x = 16.34\ lbs$$
$$P_y = 25.16\ lbs$$
$$\delta_p = \frac{P_y L^3}{3EI}$$

Where:

$$L = 9\ in$$
$$E = 10e6\ psi$$
$$I = \frac{\pi}{64}\left(D_o^4 - D_i^4\right)$$
$$I = 2.09e-3\ in^4$$

Yields:

$$\delta_p = 0.292\ in$$

$$\delta_A = \frac{P_x L}{AE}$$

Where:

$$L = 9in$$
$$I = \frac{\pi}{4}\left(D_o^2 - D_i^2\right)$$
$$A = 0.086\ in^2$$
$$E = 10e6\ psi$$

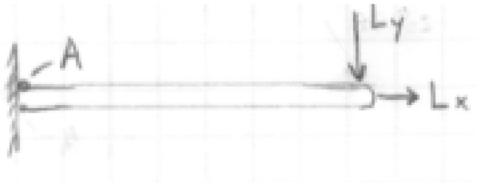
Yields:

$$\delta_A = 1.71e-4\ in$$

Max Deflection:

$$\delta = \delta_A \sin 33 + \delta_p$$
$$\delta = 0.292\ in$$

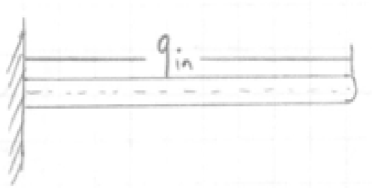
2. **Stress in Footrest**
   Assume: direct shear is negligible because the member is slender.
   Stress at pt. A:



$$\sigma = \sigma_{Axial} + \sigma_{Bending}$$

$$\sigma_{Axial} = \frac{P_x}{A} = \frac{16.34\ lb}{0.086\ in^2}$$
$$\sigma_{Axial} = 190\ psi$$
$$\sigma_{Bending} = \frac{Mc}{I} = \frac{[(25.16lbs)(9in)](0.25in)}{2.09e-3\ in^4}$$
$$\sigma_{Bending} = 27\ kpsi$$
$$\sigma = 190psi + 27086psi$$
$$\sigma = 27.2\ kpsi$$

3. **Natural Frequency of Footrest**



$$\omega_{n_1} = (l\lambda)^2\sqrt{\frac{EI}{m_e L^3}}$$

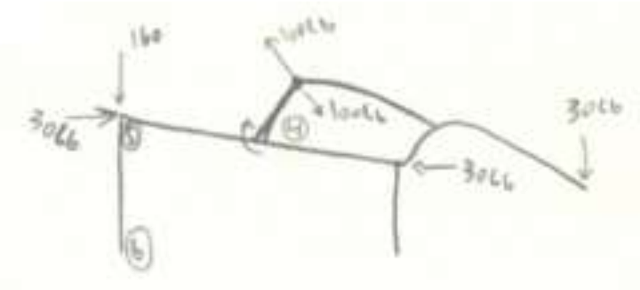
$$m_e = 0.23(\rho_{alum} A l)$$
$$(l\lambda)_1 = 1.875$$
$$(l\lambda)_2 = 4.694$$
$$(l\lambda)_3 = 7.855$$

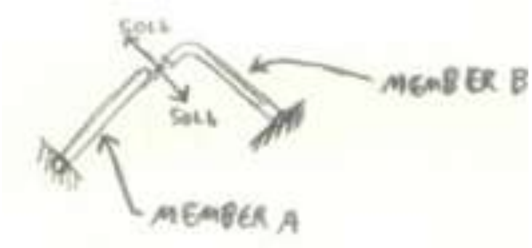
$$E = 10e6\ psi$$
$$I = 2.09e-3\ in^4$$
$$\rho_{alum} = 3.04e-3\ \frac{slug}{in^3}$$
$$m_e = 0.23\left(3.04e-3\ \frac{slug}{in^3}\right)(0.086\ in^2)(9\ in)$$
$$m_e = 5.41e-4\ slug$$
$$\omega_{n_1} = (1.875)^2\sqrt{\frac{(10e6\ psi)(2.09e-3\ in^4)}{(5.41e-4\ slug)(9\ in)^3}}$$
$$\omega_{n_1} = 1495\ \frac{rad}{sec}$$
$$f_1 = \frac{\omega_{n_1}}{2\pi}$$
$$f_1 = 446\ Hz$$
$$f_2 = 2796\ Hz$$
$$f_3 = 7830\ Hz$$

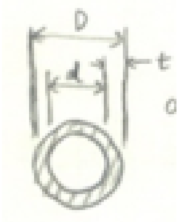
Assuming 1/16th inch wall thickness

4. Stress analysis at seat support joint

Stress on Member A:







$$M = (50lbf)(8in) = 400\ ft-in$$

$$\sigma = \frac{Mc}{I} = \frac{(L)(F)\left(\frac{D}{2}\right)}{I}$$

$$\sigma_{.5} = \frac{(400\ ft-in)(.25in)}{0.0021\ in^4} = 47619\ psi$$

$$\sigma_{.75} = \frac{(400\ ft-in)(.375in)}{0.00804\ in^4} = 18654\ psi$$

Stress on Member B:

Mostly axial compression and tension

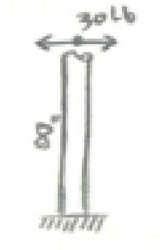
$$\sigma = \frac{P}{A} = \frac{50lb}{\frac{\pi}{4}(D^2 - d^2)}$$

$$\sigma_{.5} = 582\,psi$$

$$\sigma_{.75} = 370\,psi$$

5. **Forward/backward deflection of seat supports**

Deflection:



$$\delta_{max} = \frac{PL^3}{3EI}$$

$$\delta_{max,.5in\,al} = ((30lb)(8in)^3/(3(10e10^6)(0.0021\,in^4))$$

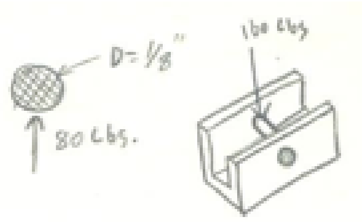
$$\delta_{max,.5in\,al} = 0.244in$$

$$\delta_{max,.75in\,al} = 0.0637in$$

$$\delta_{max,.5in\,steel} = 0.0813in$$

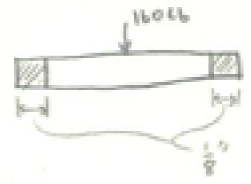
$$\delta_{max,.75in\,steel} = 0.0212in$$

6. Shear and bending stress on the pin



Direct shear on one cross section:

$$\tau = \frac{P}{A} = \frac{80lbf}{\frac{\pi}{4}(.125)^2} = 6519\,psi$$



Bearing stress on holder of pin:

$$\sigma = \frac{P}{A} = \frac{80lbf}{(.125)^2} = 5120\,psi$$

7. Fatigue on footrest

Legs modeled by a load alternating from 30 lbs downward to 0 lbs. Footrest is assumed to be a 12 inch long 1 inch diameter cantilevered tube made of 6061 aluminum.

$$Se' = 0.4Su$$

$$Se' = 0.4(42000\,psi)$$

$$Se' = 16800\,psi$$

$$Se = K_a K_b K_c K_d K_e K_f Se'$$

$$K_a = a * Su^b$$

$$K_a = 2.7 * (42\ ksi)^{-.265}$$

$$K_a \approx 1.00$$

$$d_e = .37 * d = (.37) * (1in) = .37\ in$$

$$K_b = 0.879 * (.37\ in)^{-.107}$$

$$K_b = 0.978$$

$$K_c \approx 1.00$$

$$K_d \approx 1.00$$

Reliability factor for 99% reliability:

$$K_e = 0.814$$

$$K_f \approx 1.00$$

$$Se = (1.00)(0.978)(1.00)(1.00)(0.814)(1.00)(16800\,psi)$$

$$Se = 13374\,psi$$

$$I = \frac{\pi}{64}(D^4 - d^4)$$

$$I = \frac{\pi}{64}[(1\ in)^4 - (1 - 2 * 0.049in)^4]$$

$$\sigma = \frac{Mc}{I} = \frac{(L)(F)\left(\frac{D}{2}\right)}{I} = \frac{(30\ lb)(12in)(0.5in)}{(0.04609\ in^4)}$$

$$\sigma = 3667\,psi$$

Using the Modified Goodman failure criteria, the factor of safety guarding against failure due to fatigue is:

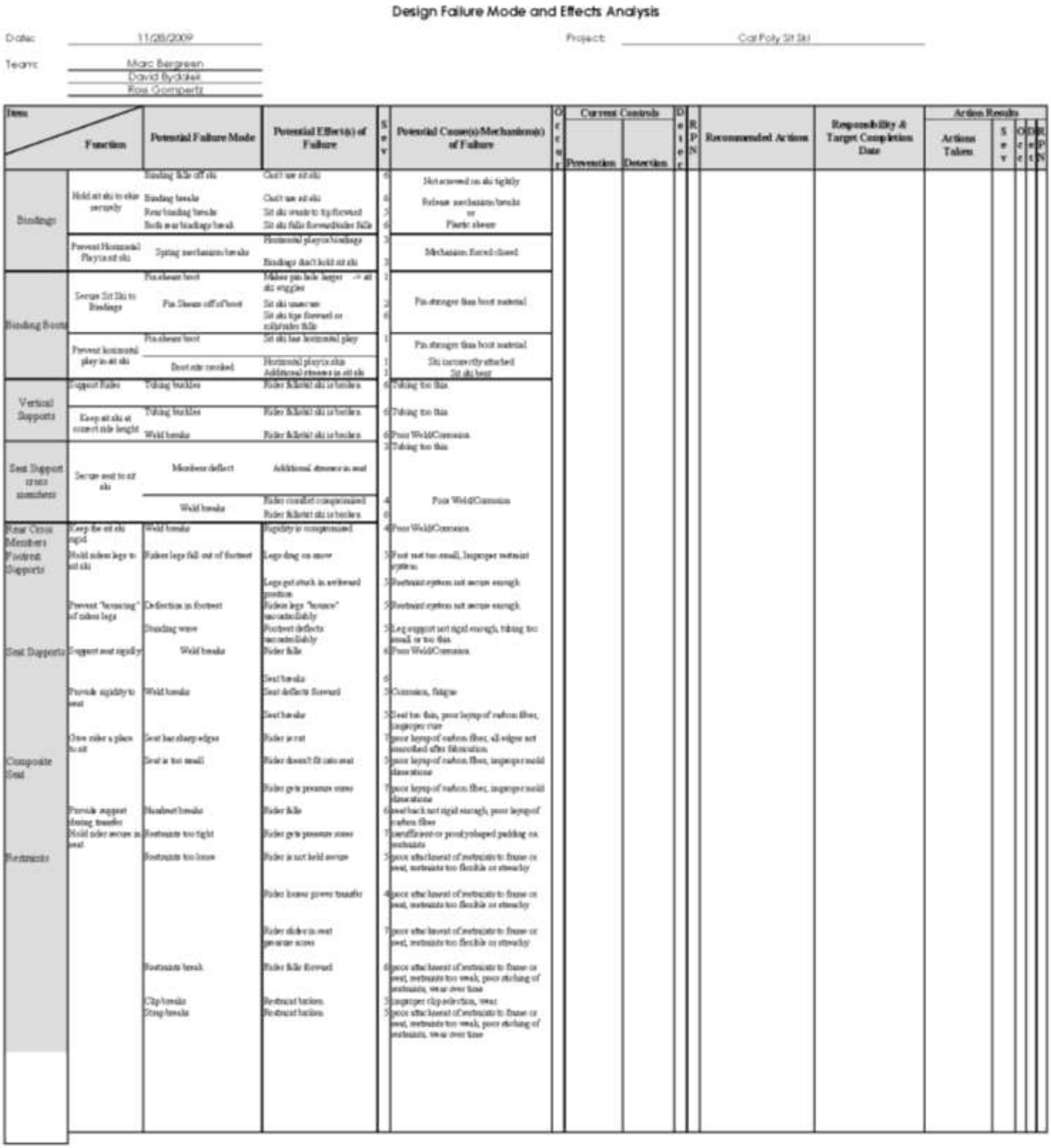
$$n_f = \frac{1}{\frac{\sigma_a}{Se} + \frac{\sigma_m}{Sut}}$$

$$n_f = \frac{1}{\frac{1834psi}{13374\,psi} + \frac{1834psi}{42000psi}}$$

$$n_f = 5.53$$

Appendix E

Design Failure Mode and Effects Analysis (FMEA)



Design Failure Mode and Effects Analysis

Date: 11/28/2009

Project: Cal Poly Sit Ski

Team: Marc Bergreen
David Bydalek
Ross Gompertz

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s)/Mechanism(s) of Failure	Occur	Current Controls: Prevention	Current Controls: Detection	Detec	RPN	Recommended Actions	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	RPN
Bindings	Hold sit ski to skis securely	Binding falls off ski	Can't use sit ski	6	Not screwed on ski tightly												
		Binding breaks	Can't use sit ski	6	Release mechanism breaks or Plastic sleeve												
		Rear binding breaks	Sit ski wants to tip forward	5													
		Both rear bindings break	Sit ski falls forward/rider falls	6													
	Prevent Horizontal Play in sit ski	Spring mechanism breaks	Horizontal play in bindings	3	Mechanism forced closed												
			Bindings don't hold sit ski	3													
Binding Boots	Secure Sit Ski to Bindings	Pin shears boot	Makes pin hole larger -> sit ski wiggles	1	Pin stronger than boot material												
		Pin Shears off of boot	Sit ski unsecure	2													
			Sit ski tips forward or sideways/rider falls	6													
	Prevent horizontal play in sit ski	Pin shears boot	Sit ski has horizontal play	1	Pin stronger than boot material												
		Boot side crooked	Horizontal play in ski	1	Ski incorrectly attached												
			Additional stresses in sit ski	1	Sit ski bent												
Vertical Supports	Support Rider	Tubing buckles	Rider falls/sit ski is broken	6	Tubing too thin												
	Keep sit ski at correct ride height	Tubing buckles	Rider falls/sit ski is broken	6	Tubing too thin												
		Weld breaks	Rider falls/sit ski is broken	6	Poor Weld/Corrosion												
				3	Tubing too thin												
Seat Support cross members	Secure seat to sit ski	Members deflect	Additional stresses in seat														
		Weld breaks	Rider comfort compromised	4	Poor Weld/Corrosion												
			Rider falls/sit ski is broken	6													
Rear Cross Members	Keep the sit ski rigid	Weld breaks	Rigidity is compromised	4	Poor Weld/Corrosion												
Footrest Supports	Hold riders legs to sit ski	Riders legs fall out of footrest	Legs drag on snow	5	Foot rest too small, Improper restraint system												
			Legs get stuck in awkward position	5	Footrest system not secure enough												
	Prevent "bouncing" of riders legs	Deflection in footrest	Riders legs "bounce" uncontrollably	5	Footrest system not secure enough												
		Standing wave	Footrest deflects uncontrollably	5	Leg support not rigid enough, tubing too small or too thin												
Seat Supports	Support seat rigidly	Weld breaks	Rider falls	6	Poor Weld/Corrosion												
			Seat breaks	6													
	Provide rigidity to seat	Weld breaks	Seat deflects forward	5	Corrosion, fatigue												
			Seat breaks	5	Seat too thin, poor layup of carbon fiber, improper cure												
Composite Seat	Give rider a place to sit	Seat has sharp edges	Rider is cut	7	poor layup of carbon fiber, all edges not smoothed after fabrication												
		Seat is too small	Rider doesn't fit into seat	5	poor layup of carbon fiber, improper mold dimensions												
			Rider gets pressure sores	7	poor layup of carbon fiber, improper mold dimensions												
	Provide support during transfer	Headrest breaks	Rider falls	6	seat back not rigid enough, poor layup of carbon fiber												
Restraints	Hold rider secure in seat	Restraints too tight	Rider gets pressure sores	7	insufficient or poorly shaped padding on restraints												
		Restraints too loose	Rider is not held secure	5	poor attachment of restraints to frame or seat, restraints too flexible or stretchy												
			Rider loses power transfer	4	poor attachment of restraints to frame or seat, restraints too flexible or stretchy												
			Rider slides in seat pressure sores	7	poor attachment of restraints to frame or seat, restraints too flexible or stretchy												
		Restraints break	Rider falls forward	6	poor attachment of restraints to frame or seat, restraints too weak, poor stitching of restraints, wear over time												
		Clip breaks	Restraint failure	5	improper clip selection, wear												
		Strap breaks	Restraint failure	5	poor attachment of restraints to frame or seat, restraints too weak, poor stitching of restraints, wear over time												

Appendix F

Design Verification Plan and Report (DVP&R))

DESIGN VERIFICATION PLAN AND REPORT

TEST PLAN											TEST REPORT			
Item No	Specification or Clause Reference	Test Type	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
							Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Weight	Objective	Place the ski on a scale	< 10 lbs	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 8 lbs	1	0	Weight of frame, seat, and bindings; doesn't include skis.
2	Vertical ski deflection	Objective	Place 80lb vertical load on ski at the bindings on one side, fix the other side and measure the linear deflection in the ski.	< .5 in	CPSS team	PV	1	C	5/24/2010	5/24/2010	Not Performed	NA	NA	Test not perfomed for fear of bending the frame. Did not have adequate fixturing to apply the load without causing excessive frame bending.
3	Horizontal ski deflection	Objective	Place 60lb horizontal load on ski at the binding on one side, fix the other side and measure the linear deflection in the ski.	< .5 in	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 0.25 in	1	0	Deflection at max was 0.25 in; average deflection was closer to 0.125 in.
4	Angular ski deflection	Objective	Place 5lb horizontal load on ski tip on one ski, fix the frame and measure the angular deflection in the ski centerline.	< 5 deg	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 0.2 deg	1	0	Angular deflection was measured to be 1/16 in over 18 in. This gives an angle of less than 1 deg.
5	Angular ski roll	Objective	Place 5 ft-lb torque on the ski, fix the frame and measure angular deflection in the ski	< 3 deg	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 3 deg	1	0	Anfular deflection was measured to be 5/8in over 12 in.
6	Time to remove skis	Objective	Use a stopwatch to time the removal of the skis	< 1 min	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 15 sec	1	0	Skis were set on a bench and frame was mounted into the 4 NNN bindings.
7	Time to attach self to ski	Objective	Use a stopwatch to time how long it takes athlete to attach himself	< 2 min	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 30 sec	1	0	Ski attach
8	Deflection of foot rest	Objective	Place 30 lb vertical load on foot rest, fix the bindings and measure the linear deflection in the foot	< .25 in	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass 3/16 in	1	0	30lbs of weight were applied to the footrest while the skis were held fixed. The deflection was measure at the main footrest tube.
9	Restraints	Objective	Hold the frame and seat steady, place 50lb load on closed restraints, check for failure.	No failure	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass	2	0	A 50lb weight was hung from the straps on the seat while the seat was suspended upside down.
10	Number of sharp edges	Possibly Subjective	Feel for any sharp edges that could contact the rider during	0 edges	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass	All	0	No sharp edges exist that could contact the rider during skiing
11	Number of pressure points or hot spots	Possibly Subjective	Feel for any pressure points or sources of rubbing while riding the	0 edges	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass	All	0	No pressure points that could cause hot spots were found.
12	Restraints	Subjective	Check that restraints hold the rider securely	Rider approval	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass	All	0	Restraints held the rider securely during the roller ski testing.
13	Stability	Subjective	Ride ski to test for tipping during turning and skiing	Rider approval	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass	0	1	Frame bent during side loading on roller skis. Frame was mounted on roller skis and bent during a dynamic turning side load.
14	Ability to right yourself	Subjective	Strap athlete to the ski, lay them on their side and allow them to	Rider approval	CPSS team	PV	1	C	5/18/2010	5/18/2010	Pass	1	0	Frame was set on floor, rider tipped ski on side and then the rider righted themself.
15	Seat comfort	Subjective	Road test with roller skis	Rider approval	CPSS team	PV	1	C	5/24/2010	5/24/2010	Pass	1	0	Seat was comfortable during testing.

Appendix G

Team Roles and Responsibilities

Marc Bergreen:

- Point of Contact for:
  - Dr. Kevin Taylor
  - Theresa Field
- Proofreading
- Research
  - Seats
  - Bindings
- Materials Schedule Management
- Report Writing

David Bydalek:

- Point of Contact for:
  - Jon Kreamelmeyer
  - Marlon Shepard
- Document Template Generation
- Research
  - IPC Rules
  - Patents
- Restraints
- Report Writing

Ross Gompertz:

- Point of Contact for:
  - Prof. Sarah Harding
  - Dr. Brian Self
- Meetings
  - Agendas
  - Minutes
- Research
  - Seat design
  - Frame
  - Nordic Course
- Report Writing

Appendix H

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