Mobile Opera Backdrop

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Mobile Opera Backdrop: Final Review Design

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Abstract

Opera San Luis Obispo requires an acoustically projecting stage backdrop for their future plan of deploying a mobile opera house. The custom stage backdrop must be low-cost, easy to assemble and must project the performance sound to outdoor audiences. Other design requirements include being transportable in a step van, the ability to be assembled quickly by a crew of two, resistance to various outdoor conditions, the ability to mount accessories from the walls, and should meet a budget of $5,000. With the scope of the project understood, the three-quarter project is outlined. During the first quarter, the main deliverables included the scope of work and the preliminary design review. During the design process, a variety of brainstorming sessions were held to develop ideas, while decision matrices yielded the superior full design concept. Based on the ideation activities and evaluations performed, the design will be a collapsible aluminum frame that uses ball-bungees to attach to a grommeted polyester coated vinyl tarps. In preparation for the Preliminary Design Review, analysis of all major components of the design was performed in order to propose a final design with all materials, dimensions, and manufacturing processes identified. Inquiries were made to several manufacturing companies and cost estimates were obtained for the custom manufactured pipes, endplates, connectors, and vinyl tarps required. Parts were then ordered to commence the manufacture phase and testing of components. Manufacturing and testing began, taking advantage of the facilities and equipment available on-campus to cut the pipes to size, drill holes, and water-jet cut the endplates. Throughout the manufacturing process, components and subassemblies were tested to validate the design and mitigate possible safety concerns. Adjustments from these sessions were made to refine the final design and assembly procedure. With the refinements finalized, the final design was presented on June 1, 2018 at the Cal Poly’s Spring 2018 Senior Project Expo.
Chapter 1: Introduction

Opera San Luis Obispo is one of four Grand Opera companies in California, providing performances consisting of orchestras, choruses, and ballets among other productions. Currently Opera San Luis Obispo is in the early stage of creating a “Mobile Opera House” which will allow the organization to perform outdoor educational and marketing outreach at various events. In order to expand connections throughout the San Luis Obispo community, Opera San Luis Obispo has sought the aid of California Polytechnic State University, San Luis Obispo to solve one of their current issues. Currently, Opera San Luis Obispo is in search of equipment which they intend to utilize for their mobile opera house. However, they cannot easily purchase a stage backdrop that meets their requirements. On behalf of Cal Poly San Luis Obispo, the senior project team consisting of Kevin Valencia, Juan Villalobos, and Robert Behlman has been tasked to construct a custom stage backdrop to meet Opera San Luis Obispo’s specifications. With the design, Opera San Luis Obispo aims to be able to efficiently deploy the final product at farmer’s markets and mid-state fairs amongst other outdoor events in an effort to educate and entertain the public through their performances.

Chapter 2: Background

Attaining an accurate understanding of the project requirements is a critical step in the design process, which entails inquiries and research to be performed. One of the most crucial steps in the design process begins with requesting information from the customer regarding the functions, dimensions, and limitations of the product. The design team should have a basic set of parameters which will guide whether their design could consist of certain elements which will still meet the requirements. In addition to the information the customer can provide, research of other existing products should be done as a guide for one’s own design. An entirely new design or product need not be created. Instead, existing products can be analyzed to determine successful designs and possible ways to improve other useful ones. Although this process might consume a considerable amount of time, it is key to focus the time, money, and effort of the team on the exact problem the customer seeks to be solved.

2.1 Customer Needs

In order to fully understand the goals and requirements of this project, phone and e-mail conversations were held with Mr. Alhadeff, in which he provided necessary background information. In order to combat the sound interference issue associated with performing in a highly crowded public area, the final product must be constructed of a sound reflective material. In addition, the sponsor has specified that the backdrop be constructed as a shell configuration to aid projecting sound towards the audience. To date, the dimension parameters are subject to change, but we estimate the backdrop to be 16 ft. in length, 12 ft. in height, and extending 4 ft. into the stage floor. The stage floor will be approximately 32 in. high, but the backdrop will be stationed on the ground. While most dimensions are subject to change, the height of backdrop is more limited since it must conceal a step van that will be located behind it. In addition, there
must be an appropriately sized passageway in the center of the backdrop which the performers will utilize to enter the stage from the van. In terms of assembly, a crew of 2 people must be able to deploy the backdrop within an hour. Also, the backdrop should be able to be loaded and transported in a step van, which will have space occupied by other equipment. Once assembled, the backdrop must have the ability to mount accessories onto the walls and ceiling, while resisting winds up to 30 mph. The backdrop does not require an extravagant design given that a simple and well-finished product can be considered visually satisfactory to the sponsor. The information obtained from Mr. Alhadeff is included in Appendix A.

In addition to the original requirements set by our sponsor, a few more minor adjustments were requested during our Critical Design Review meeting with Mr. Alhadeff. The main requirement was that the backdrop have a channel in the back of the structure, through which a pianist will have a line of sight and can synchronize his audio to the performance. The other adjustment was that the stage, backdrop, and the rear bumper of the van have minimal distance between one another.

2.2 Existing Products

In order to analyze what solutions exist for our project, we researched and benchmarked currently available designs and products. We researched a couple of products produced by Wenger Corporation, a company that provides acoustic products in the form of inflatable shells, mobile stages, and individual acoustic panels.

![Figure 1. Wenger legacy classic acoustical shell](image)

Figure 1 shows the Wenger Legacy Classic Acoustical Shell [1]. This shell is made up of a few durable, lightweight panels. The panels can reach a fully extended height of 15 feet. The formed ABS panels are easy to store. The panel-formed shell is great to project acoustical sounds in an interior or exterior stage environment. Using the panels seems like the most efficient and aesthetically appealing solution but the price for each panel is a deterrent. With each panel costing about $1600 per panel, Opera San Luis Obispo would require at least 12 to 15 panels.
Figure 2 shows a second product produced by Wenger, the Inflatable Acoustical Shell [2]. This product meets many of the required needs presented by Opera San Luis Obispo. It is easy and fast to assemble, being fully inflated in less than 10 minutes. It has been acoustically tested to improve sound projection and increase reflected sound energy. It is available in over 20 exterior colors and 3 interior colors, and comes in 3 sizes. Storage is simple, being placed in a five foot diameter bag when deflated. A useful quality that that shell has is that it is composed of vinyl-coated nylon that is weather-resistant and 100% fire retardant. As a result, the material that the shell is made of is one which will have a high consideration when we decide on materials. However, a negative aspect about this product is that hanging objects as Mr. Alhadeff would like would likely distort the shape of the shell. Also, since the shell is inflatable, a fan will need to be kept operating, producing sound interfering with the performance. The price of the shell is not specified, but based on the price of the Wenger Legacy Shell, this product will surely exceed our budget.
The Showmobile Mobile Stage in Figure 3 is another product from Wenger designed for long-term outdoor performance [3]. The Showmobile is designed to transport the entire stage from one place to another with ease. Something very creative that the Showmobile has is a push-button that allows one person to set up the entire stage in minutes. Another impressive feature is that its battery powered hydraulics system utilized to open the canopy and lower the stage, eliminating heavy lifting. It can be aesthetically appealing but it has a small performance stage area. This product does not have a price on the Wenger website, but like the inflatable shell, it would likely exceed the price of the acoustical panels.

2.3 Technical Research

The United States Patent and Trademark Office website was utilized in order to gain insight into the design of several patented products. The patents researched were for three of the products produced by Wenger Corporation, and are tabulated in Table 1.
The patents from Table 1 are successful designs which have been utilized for several years and could be modified to create improved products. These earlier patents by Wenger Corporation have been used as a reference for the existing products they currently manufacture. Similarly, it is possible to utilize the published patent information to inspire design ideation.

The patent in Figure 4 is similar to the Wenger Acoustic Shell in design and function [4]. The top panel can pivot at different angles to adjust for the audience positioning. The central panels can also adjust the overall height of the panel.
The next patent shows a performance stage which is incorporated into the side of a vehicle. The Mobile Center in Figure 5 is similar in design and can be deployed without need of removing any equipment from the vehicle [5]. This setup features a truck that contains the stage and an awning to cover the performance. This configuration is close to what Opera San Luis Obispo needs, however not enough room is left in the vehicle for carrying additional equipment.

Chapter 3: Objective

Having performed background research, the information gathered was evaluated in order to define the specifications of the design. With information provided from the sponsor, a problem statement was created to serve as a broad description of the main design requirements. Subsequently, the emphasis of the design was determined. To improve the efficiency and success of the project, each of the specifications provided by the sponsor were individually evaluated. Each specification was categorized as either a need or a want so that the team’s time and focus would be allocated toward the most fundamental specifications. The specifications were then analyzed using the Quality Function Deployment process, so that the relative importance of each specification would be determined. In addition, each specification was assigned a target value that the final design should meet and a risk of failure rating. The results obtained from these evaluation exercises produced useful results which should be kept in consideration for the remainder of the design process. These exercises identified the design specifications so that the correct problem is targeted. In addition, these exercises analyzed the specifications so that the more important ones to the success of the project are given priority.
3.1 Problem statement

Opera San Luis Obispo is seeking to expand their educational and marketing outreach through outdoor performances which currently are infeasible due to acoustic and logistic challenges. As a result, Opera San Luis Obispo needs a low-cost and easy to assemble mobile stage backdrop that will acoustically project the performance to an outdoor audience.

3.2 Needs/Wants Discussion

After processing the documents and the sponsor proposal presentation, we identified the desirable design characteristics and distinguished them between wants and needs based on our judgement. Table 2 illustrates the division of the 11 desirable characteristics into seven needs and four wants. Our classifications were assigned with consideration of our sponsor’s explicit specification and the importance of the characteristic to the design. Although not all the needs are crucial to the functionality of the backdrop, we were instructed by the sponsor that some requirements are expected for his specific product. The wants are specifications that were either irrelevant to the functionality of the backdrop, could vary based on our final design, and/or cannot be guaranteed to be satisfied. Although analytical calculations can be performed on the design and materials, it is possible that the product may not satisfy the five year lifespan goal. Analysis of different materials will be performed based on durability, but the theoretical predictions may not agree with the actual utilization. As for the budget, we intend to satisfy the initial budget, but may consider slightly exceeding it if a superior design results. The dimensions of the backdrop are also considered a want, primarily since it is subject to change. Once the sponsor provides the dimensions of the stage and the transporting van, a more accurate estimate of the dimensions will be provided. The appearance of the product is also deemed a want since the function of the backdrop is independent of its aesthetic appeal. The appearance will remain a consideration, but greater importance will be given to other aspects of the design.

Table 2 Customer needs and wants

<table>
<thead>
<tr>
<th>Customer Needs</th>
<th>Customer Wants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceals backstage vehicle</td>
<td>5 year lifespan</td>
</tr>
<tr>
<td>Acoustically projecting</td>
<td>$3500 budget</td>
</tr>
<tr>
<td>Fits in 22ft step van</td>
<td>14 ft. deployment height</td>
</tr>
<tr>
<td>Deployable by 2 people</td>
<td>Aesthetically pleasing</td>
</tr>
<tr>
<td>Stable in outdoor environments</td>
<td></td>
</tr>
<tr>
<td>Backstage access</td>
<td></td>
</tr>
<tr>
<td>Mountable walls</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Quality Function Deployment Process

The team utilized Quality Function Deployment (QFD) to identify the customer’s requirements and develop a set of engineering specifications. Quality Function Deployment is a method used by companies, in which emphasis is placed on the customer’s specifications for the purpose of improving the quality of the end-product. First, we identified the Opera San Luis Obispo performers, set-up crew, and the performance audience as the customers and our references when determining our design specifications. Next, we determined the customer requirements as interpreted from the information the sponsor provided via the project presentation proposal, email, and phone call. After listing the requirements, we also rated each requirement based on how important our team deemed each need. Our rating scale was from 1 to 5, with 5 corresponding to the highest importance. Once the needs were identified, the product specifications were determined as physical characteristics utilized to measure how well we satisfy our needs. These specifications were populated in the vertical columns in the top of the QFD house. The central grid in the middle of the QFD house was then utilized to determine the importance and relationship between each design requirement and specification. Each relationship was rated as being strong, medium, or weak. In addition, each specification was assigned a measurable design target with a corresponding importance factor to the success of the design. This was achieved by integrating the sum of the requirement-specification relationship strength factor multiplied by the importance factor for each requirement. The sum of these values for all the specifications were then normalized, yielding an overall importance factor for each specification. The QFD technique yielded results which the design team must consider during the ideation process. The importance factors of the specifications ranged from 7-14%. The panel material was the specification which resulted as the most influential design parameter. In addition, there were 4 specifications with an influential percentage of 11% or 12% which should also be given significant consideration.

Once the design parameters were identified and evaluated, the designs of products existing in the market were then analyzed and compared. Similarly, to the method discussed, the Wenger Showmobile and Wenger Legacy Shell were given a rank of 1-5 on how well they each satisfy our design requirements and specifications. The QFD house of quality is attached in Appendix B.
### 3.4 Specifications

Table 3 Specification descriptions with target values and risk ratings

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Parameter Description</th>
<th>Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Height x Width x Depth</td>
<td>14ft x 18ft x 14ft</td>
<td>+/- 1 ft</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>Sound Level</td>
<td>85 dB</td>
<td>Min.</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>Wind Resistance</td>
<td>30 mph</td>
<td>Min.</td>
<td>M</td>
<td>A,S,T</td>
</tr>
<tr>
<td>4</td>
<td>Component Weight</td>
<td>80 lb</td>
<td>Max.</td>
<td>M</td>
<td>A,T</td>
</tr>
<tr>
<td>5</td>
<td>Assembly Crew</td>
<td>2 persons</td>
<td>Max.</td>
<td>L</td>
<td>S,T</td>
</tr>
<tr>
<td>6</td>
<td>Assembly Time</td>
<td>45 min</td>
<td>Max.</td>
<td>L</td>
<td>S,T</td>
</tr>
<tr>
<td>7</td>
<td>Cost</td>
<td>$3500</td>
<td>Max.</td>
<td>H</td>
<td>A</td>
</tr>
</tbody>
</table>

As shown in Table 3, the target dimensions for the backdrop will be 14 feet high by 18 feet wide, with a tolerance of +/- 1 foot. If the stage is approximately 3 feet high, this gives a 6 foot tall actor 4 to 6 feet of head room clearance.

The sound level of the stage performance should be a minimum of 85 decibels when standing fifty feet in front of the stage. The amplification of the backdrop will be tested using scaled models to determine the product’s final shape and construction material. This will be performed in a Cal Poly Music Department sound room with the necessary recording hardware and software. The final backdrop’s amplification performance will be tested outdoors with similar equipment. There is a medium risk of not meeting this specification due to the difficulty of accurately analyzing the acoustics of the full-scale product in any outdoor environment.

The backdrop’s wind resistance will be calculated based on the surface area of the final design and will be compared to the wind resistance of products with similar geometry. A scale model will also be built and tested in the Cal Poly Wind Tunnel. With a scale model test, the team expects to receive fairly accurate results which would translate to the full scale product. There is a medium risk of not meeting this requirement based on the geometry of the design. Since the backdrop should be shell-shaped, as specified by the sponsor, drag and lift forces will tend to tilt the shell.

The weight of individual components will be analyzed based on the given component’s material and dimensions. These weights will be verified through measuring. There is a medium risk of not fulfilling this specification. While overall the backdrop will be highly modular for ease of transport, certain sections of the backdrop may still be large to reduce assembly time.
The number of crew members and the amount of time needed to assemble the backdrop will be based on the number and time needed to assemble a product of similar design. These values will be tested with the final product before customer delivery. There is a very low risk of not meeting these requirements since these will be main design goals from the start of the project.

The cost of the backdrop will be analyzed based on the backdrop’s size, necessary materials, and any specialist labor time. There is a high risk of going over the allocated budget because products of similar design and size all exceed this price point. However, coming in below the budget will be a primary focus during the design process.

3.5 Boundary diagram

The boundary diagram, show below in Figure 6, defines what components of the overall system our team is focused on. For Opera SLO’s mobile opera house, we will be responsible for the design and construction of the backdrop component of the project. We will not be working on any other part of the system. However, both the stage and step van will affect the dimensions of the backdrop. Therefore, the van and stage are immediately adjacent to our project boundary, but are not enclosed in it. Components not enclosed by the boundary include speakers, lights, props, generators and/or solar panels, etc.

Figure 6 Boundary diagram displaying the focus of our design project
Chapter 4: Concept Design Development

4.1 Concept development process & results

The concept design development process began with the generation of ideas in several group brainstorming sessions. During the first brainstorming session, the technique known as brain-sketching was utilized. During brain-sketching, the team sits in a circle and discuss the problem statement so that there is a common understanding. Once prepared, the team sets a five minute timer and each member draws a sketch of a possible solution to the problem statement. When the 5 minutes are complete, each team member stops drawing their ideas and pass their sketch the person on their left. A second round is repeated, where each member is given another 5 minutes to interpret the sketch they were given and incorporate any details which could add value to the original idea. Finally, a third round concludes the activity, where the sketches are passed to the left once more, allowing all members to input their thoughts on the ideas of the other members. The value of this technique is that it has the possibility of producing ideas which one individual member would likely have not considered. By having one member sketch his idea, another member’s creativity could be sparked. The second member’s imagination and experience could produce ideas the first member would not have foreseen, with the third member possibly having the same effect on ideas. When the team began the brain-sketching sessions, all three were based on the “Big Bubba” baseball batting cage, illustrated in Figure 7.

Figure 7. The “Big Bubba” baseball batting cage

The first brain-sketching drawing in Figure 8. was Juan’s idea, and the sketch placed its emphasis on the assembly of the design in order to meet the sponsor’s requirements. The idea consisted of four U-shaped piped which form a spherical shell when assembled about a common pivot point. Juan’s sketch was drawn in blue and demonstrates the general frame shape. Juan’s focus was on finding a solution to fitting the frame which would be up to 18 ft. long in the back of a step van. Therefore, Juan considered cutting the frame symmetrically into two parts which
would be bolted to reconnect the crossbars. In addition, a zipper would be used to connect the vinyl material which would also require being cut in half. After five minutes, it was Robbie’s turn to contribute to the sketch with his ideas drawn in black. Robbie’s input focused on how to connect the pivoting pipes to allow rotation. Using hinge connectors and 3-way connectors were two ways considered to serve as joints. During the final round, in green, Kevin considered ways of maintaining the pivoting crossbars their desired positions. Based on the “Big Bubba” design, Kevin proposed using connector bars which would be placed between the frame and the pivoting pipes. In addition, Kevin suggested sewing the vinyl material composed of the rectangular and triangular shapes created by the spaces between the frame pipes. In this manner, two large pieces of vinyl could be attached to the inner side of the frame and be connected together with the zipper previously proposed. From this brain-sketching activity, the team was able to cause other members to generate ideas. Although we ultimately determined that Robbie’s idea of hinged connectors were superior to his idea of fixed 3-way connectors, it was valuable that he included any idea that came to his mind. It was possible that the 3-way connector could have caused another member to reconsider the design in a way that would lead to improvements.

Figure 8. First idea generation worked as a team
The next sketch in Figure 9 was initiated by Kevin, with the focus being placed on backstage access. This sketch also drew inspiration from the “Big Bubba” design as before, and consisted of a spherical shell as the frame. To allow the performers to enter the stage from the back of the step van, a doorway cut out in the back of the frame was considered. From this idea, Juan considered placing vinyl strips as a curtain so that the audience does not have the distraction of the open doorway in the background. In addition, Juan placed three stairs behind the stage so that the performers could reach the three ft. high stage from the center or either side. Robbie then expanded on these ideas by incorporating pegboard panels hanging from one of the pivoting pipes. These pegboards will allow the users to hang relatively lightweight objects for theme decorations or lighting. In addition, Robbie indicated that a curtain would be placed directly behind the pegboards. This would be done so that the audience does not see performers until they are queued to enter onto the stage. From this sketch, each member made a small contribution, which resulted with a decent design that targeted different aspects that Juan’s sketch did not touch.

![Figure 9. Second idea generation worked as a team](image.jpg)

The third sketch in Figure 10 was started by Robbie and focused mainly on ways to hang materials and conceal the backstage area. This design was very similar to Kevin’s sketch, but differed in the way items would be able to be hung. Instead of hanging rigid pegboards, Robbie considered placing a central curtain which could be pulled up or down and held at the desired elevation. This curtain should be made of a material which would easily roll, yet support objects hung to it. Juan then considered placing similar curtains on the sides, which would be offset by a
few feet behind the central curtain. In addition, this design would utilize Kevin’s idea of a
doorway cut out from the back of the frame to allow access to and from the step van. With this
arrangement, the performers could walk to the empty space behind the stage and be concealed by
the central pegboard panel. When it is time to go on stage, the performers would enter from
either the left or right side of the stage.

During the second ideation session, the team utilized the S.C.A.M.P.E.R. technique in
order to analyze an already existing product which we could base our design around.
S.C.A.M.P.E.R. is an acronym which stands for substitute, combine, adapt, modify, put to
another use, eliminate, and reverse. The essence of this technique is to evaluate existing designs
and products, with the goal of generating a new design by simply making a few alterations. The
design team decided to evaluate the baseball batting case known as “Big Bubba”, which had
been a design of interest since the early stages of the design process.

Figure 10. Third idea generation worked as a team
For the substitution part of S.C.A.M.P.E.R., the team considered making material replacements that would better suit the backstage function. One replacement was replacing the net used in the batting cage with a thick foldable vinyl which would serve to reflect sound toward the audience. Another possible substitution, could be the frame material. The batting cage analyzed uses aluminum for its frame, but we could utilize a different aluminum alloy, metal, or a composite material. Next, we considered how we could combine other parts and mechanisms to the batting cage design. We could incorporate mountable pegboards which would hang vertically from the pivoting crossbars so that objects could be hung. Another combination could be telescoping the verticals of the pivoting pipes. This could be done in order to minimize the frame dimensions and amount of material used, and yet attain the desired total height of the shell.

During the adapt section, the batting cage is evaluated to determine if it could be altered to provide the function of another existing product. The Wenger panels discussed earlier had angled side and roof panels at settings of 15, 30, and 45 degrees. The batting cage design could be adapted by changing its geometry. Calculations could be performed to determine how much longer the radius of the front pivoting pipe should be than the other pivoting pipe in order to create an angled roof, for example. As for modifications, there are a couple that would improve the batting cage design to suit the team’s purpose. One modification that will likely be made is the final height of the collapsed frame. There are three heights that have been considered, being six and a half feet, three feet, and ground level. The frame height could be designed so that the performers could simply walk through a doorway, the frame and stage are flush with each other, or the frame is completely collapsible for easier loading. Another modification could be to create an angle between the stage and the sides of the shell. This would be done so that the audience viewing angle is increased and the sound is projected towards the sides as well. Another modification considered was to divide the batting cage shell into 2 or more pieces. This would allow for an easier manufacturing process and make loading the shell into the step van possible.

By putting the baseball cage’s function to serve as a stage backdrop, the team facilitates the design process drastically. Performing basic research, many specifications and an assembly drawing was obtained which could serve as a reference when creating a slightly modified design for the backdrop. Rather than creating an entirely new design, a proven concept can be utilized as a guide. However, there are some components from the batting cage design which could be eliminated. In Figure 7. above, one can see that the front pivoting pipes have a different pivoting mechanism to that of the other two pivoting pipes. The front pipe pivots so that it drops down from a horizontal position when collapsed, to a vertical assembled position. In the process, the drop-down bars add unnecessary width and material to the design. As a result, the front pivoting pipe will likely be removed. In addition, the green triangle created by the vertical underneath the rear pivoting joint and the wheel at the front of the frame would be removed to reduce the width of the design further. The wheels would also be removed entirely since the frame will require to be disassembled and will only be moved a few feet from the van to its assembly location.

The S.C.A.M.P.E.R. technique is a valuable tool which used an existing product to aid in the design of a new product. With S.C.A.M.P.E.R., the team was able to consider ways of modifying a product,
and apply it to a problem in a seemingly unrelated field. Unless there existed major foreseeable issues

with adapting an already conceived concept, it would be unnecessary to create an original design. The final idea generation session was held so that morphological analysis could be performed as a team. Morphological analysis was a method used to create ideas based on brainstorming for quantity, rather than quality. For this exercise, the scope of the design was divided into five main categories: frame structure style, frame material, acoustic material, panel attachment method, and storage method. Figure 11 demonstrates how as many ideas that could be generated were used to populate the morphological table. The ideas considered should not be evaluated or criticized during this process. As many ideas should populate the morphological table so that the number of possible design concepts increases when combinations of the five categories are developed.

From the morphological analysis, the team was able to develop three main design concepts. The first design concept would consist of a joint connected steel pipe frame, with vinyl for the acoustic material, and hooks for the panel attachment method. Figure 12 illustrates a rough sketch of this design. The frame structure would be inspired by the baseball batting cage evaluated using the S.C.A.M.P.E.R. method and would be constructed of steel. Based on the batting cage design, the frame will be collapsible due to nearly concentric joint locations allowing the bent steel pipes to pivot. The frame would take the form of an eighth of a sphere shell when the pivoting pipes are placed in their final assembly positions. In addition, the frame would be able to be disassembled and reassembled with a number of straight and T-elbow joints. Since the frame should allow for objects to be hung on a pegboard, hooks could be attached to the top of the pegboards and hung from the
crossbars of the frame.

The second idea generated from the morphological table was an aluminum shell, composed of smaller hinged aluminum panels. Figure 13 illustrates how there would be two side panels and one panel hinged to the central backdrop panel. Both the side and roof paneling would require a locking mechanism, so that the panels could remain at a specified angle with respect to the central panel. The acoustic material for this design would not require flexible properties given that they would be attached to rigid aluminum panels. As a result, panels of plexiglass could be attached to the frame for two reasons. Those reasons are that the plexiglass may be a superior sound reflector and also the frame would require additional weight to resist winds and bending. However, one of the greater challenges of this design originates from the roof panel’s hinge. The roof panel’s hinges will be subjected to relatively substantial forces, moments, and stresses due to the weight of lights installed on the roof and the weight of the panel itself. Another possible challenge of this design would be providing the ability to hang objects from it. One possible method of mounting pegboards would be by using velcro on the pegboards and on the plexiglass in the background. This design would be using simple concepts to create a functional product, however it has several challenges that make it inferior to the first morphological analysis concept.

Figure 12. First morphological concept
The third design concept that the morphological analysis yielded was a design intended to replicate the aluminum shell design, while addressing some of the flaws the aluminum shell design had. The third design, shown in Figure 14, is a frame made of elbow jointed PVC pipes and zip-tie attached vinyl. This design is a hybrid version of the two previous morphological analysis designs. The frame will have the ability to be disassembled into individual PVC pipes and reconnected with 90 degree elbow and 4-way elbow joints. Vinyl would be used once more as the acoustic material. A rectangular vinyl sheet would be attached to the central, ceiling, and two side panels. Similar to the baseball batting cage design, the vinyl could be attached to the PVC frame with grommets punched along the vinyl’s edges and zip-ties used to wrap around the pipes. Unlike the aluminum shell design, this concept would allow pegboards to be attached to the top horizontal pipe of the central PVC panel. While this would solve the pegboard attachment issue, it would have the same flaw of being subject to failure when weight is added to the horizontal pipe of the roof panel. If the weight is too large and the material strength of the PVC pipe or its elbows are too low, either the pipe or the joint may fracture.
4.2 Concept selection process & results

After morphological analysis was performed to create possible design ideas, the selection process began by limiting the ideas in the morphological table to only feasible ideas. Initially, unrealistic ideas were included in order to not exclude the possibility of a brilliant idea. However, at this stage, a possible final design should be the goal. With a restructuring of the morphological table categories used during ideation, along with the reduced number of ideas, Figure 15 shows the updated morphological table.

These concept designs were then analyzed using two Pugh matrices in Appendix D. A Pugh matrix is a tool used to determine the superior idea to successfully satisfy each of the design functions. When developing a Pugh matrix, the top idea for each function is selected by
the team, and is set as a reference. Then, all the other feasible ideas to successfully perform that same function are each compared to the reference idea. For one Pugh matrix, the acoustic fabric and the fabric attachment method were analyzed. Canvas and plexiglass were compared to a reference vinyl material. Also, zip-ties and velcro were compared to a grommet attachment reference. In the Pugh Matrix in Appendix D, each material was judged on how well it would successfully satisfy the scope requirements compared to the reference. The ratings used were a positive sign, a negative sign, or an ‘S’. The ratings were given based on whether the idea being evaluated performed better, worse, or the same, respectively, with respect to the reference idea. From the results of the Pugh matrix, we determined that the superior acoustic material and attachment method would be vinyl and velcro, respectively. The results regarding fabric material agreed with our judgement prior to filling the Pugh matrix. The Pugh matrix further solidified the team’s intuition that vinyl is the optimal material, yet will remain open to other considerations. On the other hand, the Pugh matrix determined that the grommet fabric attachment method would be outperformed by velcro. Upon reconsideration, the team was convinced that the Pugh matrix demonstrated how the team overlooked certain details when setting the grommets as the reference. The Pugh matrix convinced the team in this scenario, however, should not necessarily do so in every instance.

For the second Pugh Matrix in Appendix D, the pegboard attachment method was evaluated. A reference of a pegboard connected with metal clamp and bolts was set. Two other designs were then compared to this reference. Those ideas involved using hooks and zip-ties to allow the pegboards to hang from a crossbar. The idea utilizing hooks matched or over-performed the reference design based on the Pugh matrix and convinced us of its potential success. As for the zip-tie idea, this concept either matched or under-performed the reference concept. As a result, the team decided to utilize pegboards with hooks attached along its top edge to allow the pegboards to hang from the frame’s horizontal pipes.

With the materials, attachment methods, and frame storage methods ranked by the Pugh matrices, the weighted decision matrix in Appendix D, was created to create five full concepts. The five concepts had many similarities with one another since they were based on the highest ranked ideas from the Pugh matrices. For the weighted decision matrix, the project requirements populated the columns, while the design concepts populated the rows. The importance of each requirement being met was given a rank from one to five, with five being the most important. Then, each concept was also ranked from one to five on how successfully they satisfied each requirement, with five representing very successful. Since the importance the design requirements vary with respect to each other, a “weight” row was inserted in the decision matrix to rank their importance also from one to five. The value in the weight row is then multiplied with each value in the rows below it. When this procedure is performed for each design requirement, summing these values across each row yield the results of the weighted decision matrix. This procedure produced three competitive designs and two which could be disregarded. The scores of the three higher scoring designs were 147, 147, and 146. To evaluate these results and determine the top choice, the team used intuition and reconsider the rating values assigned. As a result, a collapsible aluminum frame, with velcro attached vinyl, and hook attached aluminum pegboards would be used. The results attained by this method were consistent with the team’s intuition and was an organized way to provide rankings.
4.3 Concept modeling

After comparing and analyzing the concept ideas that our team came up with, by using the Pugh matrix and morphological matrix above, we narrow down our ideas and now it was time to start building our prototypes. The first prototype that our team built was a more general and simple backdrop with a more box shape design as seen in Figure 16. This concept will easily hide the step van in the background. On this prototype you can easily see where the backstage entrance door would be located. Our team agreed that this prototype design was acoustically appealing but would be difficult to assemble within the hour setup limit given. The reason this prototype would be difficult to assemble is that it would be composed of one large back panel and two side panels hinged to each other making it hard to be stored in the step van.

Figure 16. Box shape backdrop prototype model

The second prototype model that our team came up with was built using clear plastic tubing. The inspiration to build this prototype came from observing “Big Bubba” batting cage. This prototype proved to be a challenge when assembling it, because it was not as stable or rigid as we would have wanted it to be. The prototype in Figure 17. has a more round shell like shape design as the design that our team is aiming for our final model to have. Two support bars had to be used to keep each hoop frame stable and equally spaced out. For this concept the fabric material would be attached by sections. In this case vinyl would be used to help amplify the sound and give the backdrop an appealing look.
Figure 17. Round shell backdrop model using clear tubing

Figure 18 shows our third prototype model. This prototype was a concept that merged both our previous concepts mentioned above. This backdrop has a round shell like shape when seeing it from a side view but it also gives that general backdrop box shape from a front view. This prototype resembles a lot of the design of “Big Bubba” where it uses a pivot system to assemble and disassemble the backdrop. The vinyl fabric will be attached by sections using either velcro or straps.

Figure 18. Backdrop model built out of wooden skewers
The third prototype concept was constructed as a 12 to 1 Solidworks model, as seen in Figure 19. The functionality, aesthetics, height and width were favorable, however the model was too deep and would close off the stage to viewers to the side of the performance.

![Figure 19](image_url)

Figure 19. Collapsing shell model that is too deep and would block the view of the performance

After further discussions and sketches our team came up with the best solution that would involve the previous concepts. We kept the same concept design but slightly modified the shape of it. Our final concept that we decided would provide the best solution was a modification of all the concepts put together as seen in Figure 20. This concept satisfies all of the requirements that the problem statement listed the prototype is able to assemble and disassemble by a pivoting system. The backdrop is aesthetically appealing and has a shell like shape. The depth had to be cut down and after a simple modification the backdrop only covers less than five feet of the stage’s side. In order for this to work we used the same pivot system but now instead of being on the ground it was lifted six and a half feet. By lifting the pivoting system off the ground not only gave us that depth that we needed but it also allowed us to facilitate the storage dimensions. In this final concept model you can see how the peg board would be mounted to the backdrop.
4.4 Selected Model

The final concept model seen in Figure 21 will consist of aluminum material for the backdrop frame. The backdrop frame will include two arched cross frames that will pivot back and forth into the assemble position and stored position. Two slightly bigger arched frames will make up the base of the model. To fully describe the concept model let's start with one of the slightly bigger arched frame placed on the ground. The second arched frame will be mounted about six-and-a half feet from the ground with the aid of six support beams equally spaced apart. The pivot system will be placed at the second arched frame. The pivot system will be held together with a steel end plate to give the pivot system a better support. The arched frame where the pivot system is mounted to will remain fixed while the two smaller arched frames will pivot back and forth in a circular path. Vinyl is the fabric material chosen to use for our design concept. The way that the vinyl will be attached to the backdrop frame will consist of having three different sections. The first section will be attached between the two slightly larger arched frames meaning between the ground frame and the next lifted arched frame (the base frame). The second section of vinyl will be attached between the first lifted frame and the middle pivoting arched frame. Finally the third section of vinyl fabric will be attached between the middle pivoting frame and the front pivoting frame. The vinyl sections will be attached using either velcro connections or zippers. The first section of vinyl at the base frame will have a concealed entrance so that the performers have access to the back of the step van.
4.5 Concept Functionality

The primary function of the backdrop is to project the sound of the performance. To do this, the selected concept utilizes a combination of curved and angled panels of fabric to reflect and redirect the sound waves towards the audience. The exact angles of these panels, seen in Figure 22, will be adjusted after audio testing is performed using scaled models. However, structural rigidity will be the primary design factor and aesthetics will also be heavily considered.
Another critical function of the backdrop is to obstruct the sight of the support truck from the view of the audience and to accommodate the size of the stage. The current concept measures 18 feet wide, 7.5 feet deep, and 14 feet high, as shown in Figure 23. These dimensions combined with the thickness of the fabric and the limited number of seams provides excellent visual obstruction of backstage operations. Stage shown is 16ft wide x 12ft deep. Current configuration leaves 2 ½ feet of shoulder room between the backdrop and the rear of the stage. Backstage access opening is 8 ft. wide.
The stage backdrop must be easily transportable to and from the performance location. Additionally, once on site, the backdrop must be quick and easy to assemble with two individuals. To aid with all of these needs, the selected concept has a frame made of lightweight 6061-T6 aluminum. In addition to being lightweight, aluminum is inexpensive and easy to bend and drill, all while still being very strong. To easily expand from a collapsed state to its full deployment state, the selected concept utilizes two push-arms that are used to manually lift each of the two sections into position, as shown in Figure 24.

Figure 24. Backdrop shown in the collapsed state, mid-deployment state and full deployment state.
The individual tubes of the frame are held together using aluminum connectors that utilize set screws to securely hold the tubes in position. After the backdrop has been collapsed down, it can be further broken down into smaller sections by removing any of these connectors. This allows the backdrop to have multiple storage states. If necessary, the backdrop can be reduced to individual tubes to have the absolute minimum storage size. However, for the fastest setup time, as few of these connectors should be disconnected as possible.

With the selected concept, props can be set up on the pegboard that hangs from the middle support hoop. The pegboard will be made of aluminum or plastic in order for it to be lightweight and resistant to the elements. Additionally, the pegboard will provide the function of concealing the backstage access opening, as seen in Figure 25. The hanging pegboard provides a location for props while also obstructing the audience’s view of backstage. A form of curved or angled stairs will need to be built to provide access to and off the stage.

Figure 25. Rear view of the backdrop with transparent paneling to show the backstage access opening.
4.6 Risks and Unknowns

The current concept has a few unknowns that the team will be testing for and addressing as quickly as possible. The first of these is the risk that tube alignment may be difficult to achieve during frame assembly. The current frame design consists of eight curved sections of aluminum tubing; the forming of each one of these bends can be inconsistent using the manual machines available on the Cal Poly campus. Tubes with curves of varying dimensions would lead to a crooked and weakened structure, or would be impossible to construct at all. To avoid this possibility, tube bending vendors have already been contacted and multiple quotes have been received for these critical components. However, new quotes will be requested once the design and tubing dimensions have been finalized after proper analysis has been conducted.

Another potential problem is frame rigidity. The number of tubes utilized in the frame has been minimized to reduce assembly time, weight, storage space and cost. However, analysis has yet to be done to confirm the backdrop will not flex from its own weight or when exposed to winds, leading to undesirable wobble and instability. Hand calculations and computer simulations (also known as finite element analysis, or FEA) will also be conducted to ensure the front hoop can support the weight of lighting fixtures. To guarantee the structure’s stability, bracing components will be designed before testing and will be ready for immediate implementation if so required.

One more concern with the current concept is the ease of access to and from the stage. One of the frame’s tubes runs along the top of the opening where performers will pass through the backdrop. This tube is used to support the push-arms that hold up the collapsing portion of the backdrop. In order to easily raise each of the two sections during the setup process, the height of this tube will be six feet or less above the ground. This means the two individuals setting up the backdrop do not need to raise the push-arms above their heads, which is difficult to do and also increases the risk of injury. However, this means that many performers will need to lower their heads in order to pass through the backdrop when entering or leaving the stage, especially if they are wearing some form of hat or head covering. This creates the risk that a performer may bump their head on this cross tube. The current solution is to cover this tube with a highly-visible foam pad to remind the performers’ of its presence and to reduce the effects of an impact. However, there is the possibility of modifying the frame geometry if the current solution is deemed undesirable. In addition to performers striking their heads on one of the pipes, other safety considerations are noted in the design hazard checklist in Appendix E. In this document, several possible safety risks that the users of this product are exposed to are discussed and also possible solutions to mitigate those risks.

Chapter 5: Final Design

Upon conclusion of the Preliminary Design Review (PDR) stage, further analysis and research was required to compose a final design proposal, with virtually all details finalized. This required a revised design, addressing any concerns and suggestions offered by Mr. Alhadeff. Preparing for the Critical Design Review (CDR), the system had to be analyzed in terms of subassemblies and individual components. The most critical aspects of the system were analyzed in order to justify the
use of certain materials and properties. Once the desired parts were identified, a manufacturing plan was assembled, beginning by attaining material suppliers. Knowing what parts will be utilized, the required manufacturing process services were requested from several companies. However, prior to the purchasing of parts, prototyping and testing on several critical components were performed.

5.1 Revised Design

After presenting to Mr. Alhadeff at the Preliminary Design Review and considering any suggestions, we made a few adjustments to the previous design in order to fully satisfy the requirements. While the top section (overhang assembly) of the model remained unmodified, the bottom section (base assembly) was altered from a circular base to a rectangular base as seen below in Figure 26. This change was done so that the stage would fit flush with base and unused space was minimized. In addition, the base assembly was modified by creating a gap in the rear central area. This was done since the sponsor specified during our PDR meeting that he would like to have a pianist play from within the van, which will be backed-up against the base. Another modification that was added to the design were two attachment arms (truck brace assembly) that would be connected to the truck. This adjustment was designed to reduce sway of the structure removing the possibility of it becoming air-born in the case of a high wind environment.

![Figure 26. Left: The previous potential backdrop design. Right: The final backdrop design.](image)

5.2 Overall Description & Layout

The following was the final design concept of the Mobile Opera Backdrop. The design consists of five sub-assemblies as seen below in Figure 27. These include the base, overhang, end-plate, truck-brace, and the fabric assemblies.
The overhang assembly has two arch pipes that are manually pivoted to the desired position. The base assembly's main function is as a support structure for the overhang assembly. The base assembly splits into two halves in order for the backdrop to be stored in the support truck. The endplate assembly allows the overhang assembly to be rotated to the deployed position and down again into the storage position. The fabric that attaches to the frame does not need to be removed during this process. The discussed sub-assemblies will be discussed in further detail in the following subsections.

5.3 Sub-System Detailed Design Description

5.3.1 Base

The purpose of the base is to support the overhang assembly and match its fit with the stage. The base has a rear opening to allow performers and props to move between the stage and the support truck, or allow a pianist playing in the truck to synchronize with the performance. The base assembly consists of straight pipes of different lengths. The front vertical pipes connect to the top and bottom side horizontal pipes using elbow connectors, while the outer rear vertical pipes connect to the rear and side horizontal pipes using 3-way elbow connectors. The inner vertical pipes use tee connectors to connect to the bottom rear pipe and rear center pipe. The rear center pipe is placed at a height of 30 inches to be below the height of the stage at 32 inches. To give the base more stability and reduce lateral deflection, braces connect to the sides and rear of the base assembly using adjustable angle connectors, as shown in Figure 28.
The backdrop frame is constructed from 6063-T5 aluminum pipes. Each pipe has a 1.90 in. outer diameter, with a wall thickness of 0.15 in. 6063-T5 is a grade of aluminum that is commonly used for outdoor structures due to its higher oxidation resistance compared to 6061-T6 aluminum. The balance of lightness and strength of aluminum makes it the perfect material to meet our design requirements. Although steel would have been a viable material structurally, it would make transportation of the structure much more difficult due to the significant increase in weight. In addition, by using aluminum over steel and other materials, it allows for a relatively larger pipe diameter to be used to satisfy the aesthetic appeal requirement. Steel could be used, but the cost and weight would not exceed the benefit of the structural properties advantage.
To justify the use of the proposed pipe dimensions, a buckling calculation was performed. With calculations performed in Appendix E, the total weight that the base would be subjected to was estimated. The weight of the total canvas was calculated by modelling the overhang as a quarter-spherical shell. Another generalized technique used to model the structure was to not only divide the total load across the 6 vertical base pipes, but also consider the 4 diagonal pipes as providing 71% of vertical load support as the vertical frame pipes. Utilizing a weight density of 18 ounces per square yard of the fabric, the overall tarp weight was calculated to be 31 lbf. In addition, the weight of each pivoting hoop and the push arms were measured in SolidWorks to weigh 30 and 5.5 lbf, respectively. In addition, it was assumed that the sponsor would be installing performance lights on the straight section of the pivoting hoops. We therefore included a 100 lbf load for lighting. For safety concerns, two 250 lbf loads for the scenario where two grown adults hang from the tubes were applied. Inputting these variables in the case of Eulerian beams, the buckling calculation yielded a safety factor of 117 for our given wall thickness.

5.3.2 Overhang

The function of the overhang assembly is to provide shade for the stage and protection from the elements, while also aiding to reflect the sound of the performance. The overhang consists of two arch frames and four push arms. Each of the arch frames consists of two rolled pipes and one straight pipe brought together by straight connectors. The push arms are used to manually pivot each of the arch frames into their deployed positions and connect to the arch frames using tee connectors.

Figure 30. Overhang subassembly of the backdrop
The pipes for the overhang assembly possess the same diametral dimensions as those of the base assembly in order to use the same size connectors for all subassemblies of the backdrop. The pipes are the same 6063-T5 aluminum as the base. The analysis performed to size the pipes was designed to address the most critical components, and those dimensions were then applied to the remainder of the structure.

The analysis of the overhang assembly was possibly the most critical aspect in terms of sizing the pipes used. Since the straight sections of the pivoting hoops will likely be subjected to transverse loads from lighting and decorations, this can result in significant bending and deflection of the pipes. To examine the effect of the loads, a simulation was created using a single concentrated load of 200 lbf, yielding a 1.28 inch deflection. A distributed load was not utilized, so that the simulation yields a larger deflection and a conservative maximum allowable load could be assigned. Based on the sponsor’s suggestion that four or five lights weighing approximately 5 lbf each, a maximum load not exceeding 50 lbf is recommended. As a result, a deflection of approximately 0.32 in. would result when fully loaded. An image of the FEA study performed on the entire structure, showing the deflections is available in appendix E.

5.3.3 Endplates

The endplates connect the vertical and horizontal pipes of the base frame to the overhang assembly, as shown in Figure 30. The endplates are designed to give the pivoting tubes of the overhang assembly enough clearance to complete their required rotation. Each endplate assembly will consist of two bracket plates and six bolts with nuts and washers to keep the endplates in place.

The two brackets used to make up the endplate assembly are made of ASTM A36 steel with a quarter-inch thickness. The widely available ASTM A36 steel was chosen as the material for the endplate since it is machinable, inexpensive and possesses desirable mechanical qualities. Unlike the piping structure, the endplates do constitute a large amount of weight, therefore allowing for steel to
be used. Although steel is heavier than aluminum, the final weight of each endplate was approximately 5.5 lbf. Consequently, since the endplates are critical components and they are still relatively light, it is reasonable to utilize steel. The failure of the endplates could result in complete failure of the structures functionality, and furthermore, could pose a significant safety hazard. As a result, the endplates were constructed from steel to ensure structural integrity and safety.

For the endplate, one the greatest concerns would be that it would require a large thickness in order to adequately support the structure. This would create heavy components over five and a half feet high. Therefore, Example 6-13 from Shigley’s Mechanical Engineering Design, Tenth Ed, was utilized as a reference to determine the thickness required for a plate with a hole under tensile loading. While our application subjects the endplate to compression, this example remained suitable given that steel has very similar tensile and compressive strengths, unlike other materials. The total weight utilized in the calculations included the weight of one hoop, two push arms, the overhang tarp, lights, decorations, and 2 adults as a precaution. The weight totaled 724 lbf, however, the weight would be distributed evenly by one hole in each of the four endplates. Ultimately, the effective compressive force exerted on the endplates would be a conservative 181 lbf load per hole. Accounting for stress concentration factors due to the holes in the endplate, the minimum plate thickness required was 0.00284 inch. Utilizing our proposed thickness of 0.25 in represents a safety factor of 88 for the endplate. This appears to be excessive, but is largely due to the fact that each endplate will not experience loads exceeding the relatively low loads of 181 pounds in the worst case of inappropriate use. The hand calculations performed are available in Appendix E.

5.3.4 Truck Brace

The truck brace assembly offers additional stability for the structure. The truck brace assembly was not manufactured because it is highly dependent on the truck used with the backdrop, and the truck had not yet been purchased. The support arms from the truck brace would prevent the backdrop from being lifted by the wind. The proposed truck brace is composed of two tee connectors, a straight pipe, and the truck anchor. The truck anchor is a special bracket that will allow the brace to be connected to the truck. The truck brace will be adjustable for different distances and heights between the truck and the backdrop.
The truck brace would made up of the same 1.90 inch outer diameter aluminum pipe as the rest of the frame. The proposed truck anchor would be made of two welded parts; a three inch angle iron bracket and a 1.90 inch steel tube. The steel tube welded part would be connected to the assembly using a tee connector.

5.3.5 Fabric

The fabric is one of the most crucial components of the backdrop design. The main purpose of the fabric is to help reflect and amplify the sound of the performance while creating a backdrop that aesthetically obstructs the view of the support truck. The fabric is split into 8 sections as seen below in Figure 33. All of the fabric sections attach to the frame using ball bungees that pass through grommets installed along the edges of the fabric. The base assembly is covered using two fabric sections, one for each half. The overhang assembly is covered using six different sections.
Figure 33. Ball bungees are used to connect the fabric to the frame

The fabric material used is a vinyl-coated polyester. This material was initially selected after researching the Lunar Duo reflective fabric from a company named Gerriets. The Lunar Duo is a 100% polyester fabric which has properties such as a 90% sound reflectance, ideal for our purpose. However, most of our research on reflective materials led to the conclusion that products like the Lunar Duo are only suitable for indoor studio or theater settings. The lack of UV-ray, thermal, water, and abrasion protection, coupled with the fact that reflective materials could cost multiple times that of industrial tarps, created a large risk in investing in such a product. The vinyl-coated polyester tarp was chosen due to the fact that it also is composed of polyester, and thus should possess similar sound reflective properties. In addition, the vinyl-coated polyester tarp is UV resistant, water-proof, and abrasion resistant. As a result, a compromise had to be made between the sound amplification and the durability of expensive components.

Figure 34. Final design fabric sections
One issue to consider with the fabric is that it might develop unwanted creases and wear patterns due to constantly folding and unfolding when assembling and disassembling the backdrop.

5.4 Bill of Materials & Cost Analysis

In the subsequent sections, all the components required and a cost analysis will be discussed. In addition, a bill of materials and complete drawing package regarding all the parts and assemblies is available in Appendix F.

5.4.1 Base

Table 4 below shows the components used to build the base assembly. The table also shows the cost, vendor, and the quantity of each component needed. The connectors used to hold the pipes together were purchased through an online retailer titled Buy Railings. The connectors proved to be more expensive than we anticipated, however the price is worth it due to the high quality construction of the connectors and their high resistance to corrosion. Costs were reduced by a deal on Buy Railings that saved 20% on pipe costs.

Table 4. Component and total costs of the base assembly

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<th>Component</th>
<th>Description</th>
<th>Vendor</th>
<th>Qty.</th>
<th>Unit Price</th>
<th>Total Cost</th>
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<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
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<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
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<td>$34.10</td>
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</tr>
<tr>
<td>Vertical Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>6</td>
<td>$25.57</td>
<td>$153.42</td>
</tr>
<tr>
<td>Rear Brace Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>2</td>
<td>$42.62</td>
<td>$85.24</td>
</tr>
<tr>
<td>Side Brace Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>2</td>
<td>$42.62</td>
<td>$85.24</td>
</tr>
<tr>
<td>Elbow Connector</td>
<td>Hollaender Speed-Rail, Aluminum-Magnesium Alloy 535, 304 SS set screws</td>
<td>Buy Railings</td>
<td>4</td>
<td>$16.52</td>
<td>$66.08</td>
</tr>
<tr>
<td>3-Way Elbow Connector</td>
<td>Hollaender Speed-Rail, Aluminum-Magnesium Alloy 535, 304 SS set screws</td>
<td>Buy Railings</td>
<td>4</td>
<td>$17.80</td>
<td>$71.20</td>
</tr>
<tr>
<td>Angle Connector</td>
<td>Hollaender Speed-Rail, Aluminum-Magnesium Alloy 535, 304 SS set screws</td>
<td>Buy Railings</td>
<td>8</td>
<td>$22.37</td>
<td>$178.96</td>
</tr>
</tbody>
</table>
5.4.2 Overhang

Table 5 below shows the components needed to design and build the overhang assembly. The curved pipes were rolled by Tube-Tec Bending located in Texas. Tube-Tec Bending gave the lowest quote, including the cost of freight shipping. The pipes received were properly rolled to our specifications and had minimum marks from the rolling process. We recommend reusing Tube-Tec Bending in the future.

Table 5. Component and total costs of the overhang assembly

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Vendor</th>
<th>Qty.</th>
<th>Unit Price</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch Center Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>2</td>
<td>$25.57</td>
<td>$51.14</td>
</tr>
<tr>
<td>Arch Curved Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Tube-Tec Bending</td>
<td>4</td>
<td>$97.80</td>
<td>$391.20</td>
</tr>
<tr>
<td>Push Arm Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>4</td>
<td>$34.10</td>
<td>$136.40</td>
</tr>
<tr>
<td>Straight Connector</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>4</td>
<td>$13.80</td>
<td>$55.20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$740.98</strong></td>
</tr>
</tbody>
</table>

5.4.3 Endplates (Pivot Joints)

Table 6 below shows the components needed to build the endplate assembly. A36 steel is a very common composition of steel and is commonly used in large scale construction projects. The high supply of this material makes it relatively cheap compared to less common steels. Costs were reduced by cutting the steel for free using the waterjet at Cal Poly. In the future this process could be done by a number of local metal cutting companies. The hardware was purchased from Lowes.

Table 6. Component and total costs of the endplate assembly

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Vendor</th>
<th>Qty.</th>
<th>Unit Price</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endplate</td>
<td>ASTM A36 steel, 1/4” thickness</td>
<td>GA Steel</td>
<td>4</td>
<td>$25.57</td>
<td>$102.28</td>
</tr>
<tr>
<td>Bolts</td>
<td>1/2”-13</td>
<td>Lowes</td>
<td>12</td>
<td>$1.70</td>
<td>$20.40</td>
</tr>
<tr>
<td>Nuts</td>
<td>1/2”-13</td>
<td>Lowes</td>
<td>12</td>
<td>$0.20</td>
<td>$2.40</td>
</tr>
<tr>
<td>Washers</td>
<td>1/2” 25-Count</td>
<td>Lowes</td>
<td>1</td>
<td>$6.79</td>
<td>$6.79</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$131.87</strong></td>
</tr>
</tbody>
</table>
### 5.4.4 Truck Brace

Table 7 below shows the components needed to build the truck brace assembly. This assembly may have to be altered based on the dimensions of the truck that is purchased.

**Table 7. Component and total costs of the truck brace assembly**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Vendor</th>
<th>Qty.</th>
<th>Unit Price</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracket Pipe</td>
<td>1.90&quot; OD x 4&quot; Length Steel Pipe</td>
<td>Local Metal Supplier</td>
<td>2</td>
<td>$10.00</td>
<td>$20.00</td>
</tr>
<tr>
<td>Bracket</td>
<td>3&quot; Angle Iron x 6&quot;</td>
<td>Local Metal Supplier</td>
<td>2</td>
<td>$10.00</td>
<td>$20.00</td>
</tr>
<tr>
<td>Brace Pipe</td>
<td>1.5” Sch 40 Aluminum pipe 1.90” OD x .15” wall</td>
<td>Buy Railings</td>
<td>2</td>
<td>$25.57</td>
<td>$51.14</td>
</tr>
<tr>
<td>Tee Connector</td>
<td>Hollaender Speed-Rail, Aluminum-Magnesium Alloy 535, 304 SS set screws</td>
<td>Buy Railings</td>
<td>4</td>
<td>$13.38</td>
<td>$53.52</td>
</tr>
<tr>
<td>Bolts</td>
<td>1/2&quot;-13</td>
<td>Lowes</td>
<td>4</td>
<td>$1.70</td>
<td>$6.80</td>
</tr>
<tr>
<td>Nuts</td>
<td>1/2&quot;-13</td>
<td>Lowes</td>
<td>4</td>
<td>$0.20</td>
<td>$0.80</td>
</tr>
<tr>
<td>Washers</td>
<td>1/2” 25-Count</td>
<td>Lowes</td>
<td>1</td>
<td>$6.79</td>
<td>$6.79</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$159.05</strong></td>
</tr>
</tbody>
</table>

### 5.4.5 Fabric

The fabric used was procured from MyTarps.com located in Georgia and hemmed by Mitch’s Stitches in San Luis Obispo. We cut the fabric and installed the grommets ourselves, reducing the labor costs. To replace a fabric section in the future, the worn section could be given to Mitch’s Stitches, who would be able to source the material, cut it to size, hem the edges and install the grommets. The greatest time investment and therefore labor cost would be creating the original templates, however we already completed that process. Costs could be reduced by purchasing a smaller section of fabric material. The 30’x30’ square was bought to have excess material in case mistakes were made and portions needed to be re-cut. Multiple smaller sections could be purchased to make it easier to manipulate the fabric during cutting.

**Table 8. Component and total costs of the fabric assembly**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Vendor</th>
<th>Qty.</th>
<th>Unit Price</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric Material</td>
<td>30’x30’ 18 oz. Vinyl-Coated Polyester</td>
<td>My Tarp</td>
<td>1</td>
<td>$635.98</td>
<td>$635.98</td>
</tr>
<tr>
<td>Fabric Labor</td>
<td>Hemming the fabric edges</td>
<td>Mitch’s Stitches</td>
<td>-</td>
<td>$500.00</td>
<td>$500.00</td>
</tr>
<tr>
<td>Grommets</td>
<td>General Tools 3/8&quot; Brass Grommets - 24 Count</td>
<td>Amazon</td>
<td>15</td>
<td>$3.24</td>
<td>$48.60</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------</td>
<td>--------</td>
<td>----</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>Ball Bungees</td>
<td>Sigman 6&quot; Black Ball Bungees - 100 Count</td>
<td>My Tarp</td>
<td>4</td>
<td>$23.95</td>
<td>$95.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
</tr>
</tbody>
</table>

5.4.6 Shipping Costs

Overall project costs were greatly increased by the need to pay for freight shipping for both the straight and rolled pipes. However, even without the cost of shipping local prices were still higher.

Table 9. Shipping costs of the pipes, connectors and fabric

<table>
<thead>
<tr>
<th>Component</th>
<th>Vendor</th>
<th>Shipping Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Pipes &amp; Connectors</td>
<td>Buy Railings</td>
<td>$199.00</td>
</tr>
<tr>
<td>Rolled Pipes</td>
<td>Tube-Tec Bending</td>
<td>$214.51</td>
</tr>
<tr>
<td>Fabric</td>
<td>My Tarp</td>
<td>$80.39</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$493.90</td>
</tr>
</tbody>
</table>

5.4.7 Total Cost

The total cost of the backdrop is approximately $3,900, with the cost of each subsystem tabulated in Table 10. This total does not include the cost of excess materials.

Table 10. Combined costs of the assemblies plus shipping

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>$1,037.00</td>
</tr>
<tr>
<td>Overhang</td>
<td>$740.98</td>
</tr>
<tr>
<td>Endplate</td>
<td>$131.87</td>
</tr>
<tr>
<td>Truck Brace</td>
<td>$159.05</td>
</tr>
<tr>
<td>Fabric</td>
<td>$1,280.38</td>
</tr>
<tr>
<td>Shipping</td>
<td>$493.90</td>
</tr>
<tr>
<td>Total</td>
<td>$3,843.18</td>
</tr>
</tbody>
</table>

5.5 Safety, Maintenance, & Repair Considerations

Designing the components of the structure could not be done without taking into consideration the
safety of the end user. As a result, a safety analysis was performed in the form of a safety hazards checklist and a failure modes and effects analysis, with both tables available in Appendix G.

5.5.1 Safety Hazards Checklist

During the design phase of the backdrop, safety was considered by developing a Safety Hazards Checklist (SHC) and a Failure Modes and Effects Analysis (FMEA), both documents available in Appendix G. By evaluating our design against the questions asked in the SHC, we were able to create preventative actions to eliminate or limit the effect of potential safety hazards. Several questions addressed the concern of the pivoting hoops, which likely present the largest threat to safety. As per the questions the SHC asks, the pivoting hoops can undergo high accelerations, can weigh over five pounds, could fall due to gravity, will expose the user to overhead weights, and will store energy. Due to the pinned joint on each end of the hoops, the system poses a threat should the hoop slip from one’s hand or an over-rotation swing the hoops and harm someone within a nine feet radius (16 feet long cylinder) from the endplate.

The main preventative actions to these hazards included constructing the backdrop using appropriate materials and dimensions. Each component was designed with a reasonable safety factor to reduce the risk of a failure that would threaten the integrity of the pivoting assembly. The push arms connecting the two pivoting hoops together using tee connectors limit the pivoting hazard. The tee connectors that the push arms will be connected to will have 2 setscrews rated for 200 lb loading in any direction as shown in Figure F-4 in Appendix F. Since the total weight of each hoop is 32 lb and the entire fabric weight is 31 lb, each setscrew will support the load without slipping. In addition, the hoops will be set at 50 degrees apart from one another. Although the front hoop will be set at 100 degrees clock-wise (origin at the endplate) from the horizontal, tending to rotate the system forward, the center of gravity of the entire over-hang subsystem will still remain on the left of the vertical axis as illustrated in Figure 35.

Figure 35. Side view of the structure.
The SHC also brings to question the possibility of projectiles being produced and methods of prevention. Concerning the connectors from Hollaender, the specification sheet in Appendix F states the connectors can handle a 200 lb load. The possibility of the setscrews slipping or shearing-off and leading to a projectile being launched is unlikely due to low weight of our aluminum frame and lightweight fabric.

On the topic of uncontrolled swinging weights and projectiles being launched, the endplate was also designed to prevent such events from occurring. With the endplate thickness discussed in section 5.3.3, the next concern would be the bolts. The bolts are placed under a shear load, but have a very high safety factor considering the low forces involved and the half inch diameter of the bolts. There will be a total of 12 bolts supporting the two hoops, four push arms, ten connectors, the vinyl, and lights estimated to weigh a combined 150 lb.

Another concern will be the fact that the structure will be exposed to heat, wind, and rough surfaces. Wind presents the greatest danger since the hemispherical shell creates the possibility of lift forces from the wind tipping or lifting the frame from the ground. As a result the truck-brace subsystem previously discussed will serve as an anchor. Water barrels with tie downs connecting to the backdrop could also be used. Another hazard will be the UV rays and winds that could harm the fabric material. However, the vinyl coated polyester tarp used has properties protecting against those potential hazards. Rubber pads should be placed under the bottom connectors to prevent abrasive damage to those components over time.

There always exists the possibility that the structure could be used inappropriately and the structural integrity could be questioned. However, while a couple of the calculations and simulations we performed accounted for the weight of two adult persons, a safety manual will be provided. In this safety manual, recommendation for safe loading limits will be stated and the user should abide to the recommendations. The complete Safety Hazards Checklist is available in Appendix G.

5.5.2 Failure Modes and Effects Analysis

In order to identify the possible failures and their root sources, a failure modes and effects analysis (FMEA) was performed. In the FMEA, the entire system was broken down into four subsystems; base, pivot, projection, and general. In addition, all the functions for each subsystem were identified, along with potential failure modes and causes. Once each of failure was identified, recommended actions were assigned to each team member in order to eliminate or mitigate the failure modes. In addition to identifying what failure modes exist, this tool also serves to rank the failures in terms of their likelihood of occurring. When each failure mode was being identified, a severity factor of 1 (minor) to 10 (very high) was assigned, indicating how severe a possible failure would be to the safety and satisfaction of the user. The occurrence likelihood of the failure mode was also ranked from 1 (remote) to 10 (very high). The third rating set was the likelihood that a detection method would identify a possibility of failure from 1 (very high) to 10 (almost no detection). When values of the three ratings are multiplied by one another, the highest resulting number indicates the failure mode that should likely be given priority to create a solution for. For our system, the most critical
system according to the FMEA was the projection system with the possibility of not reflecting enough sound. The selected material needed to be durable in an outdoor environment yet sound reflective. Failing to satisfy these requirements would lead either to premature degradation of the backdrop fabric or unsatisfactory sound projection of the performance. These possibilities were mitigated by testing and selecting a vinyl-coated polyester material.

Next in the FMEA process, recommended prevention actions are assigned and completed. For projection system, we recommended visiting a local fabric shop in order to seek advice on a certain material and geometry. From the visit to a local shop, SLO Sail and Canvas, they did not offer reflective material, but would provide the service of sewing the fabric into a geometry which would aid in the sound projection. In the end they did not offer this service, and instead we cut the fabric ourselves and had it hemmed at Mitch’s Stitches. In addition, research was performed on reflective materials, which showed there are polyester fabrics available that are used as reflective materials. As a result, as previously discussed a vinyl coated polyester tarp was used to simultaneously reflect sound and protect against weather conditions.

5.5.3 Maintenance and Repair

The system has few parts that require maintenance and repair, but those that do are simple. The main concern will be the connector setscrews, so it is recommended that they are checked to be fully tightened with every use. After the backdrop is setup, someone with an Allen key should attempt to tighten every set screw in every connector. This will ensure the stability of the backdrop, which is critical for the safety of the performers and the audience. For cleaning, Figure F-5 in Appendix F demonstrates some maintenance procedures for the connectors which are suggested to maintain a high quality. The nuts, bolts, and washers are stock parts and should be readily available in many hardware stores. The steel brackets should be checked for scratches in the powder coat that would lead to corrosion of the steel. As for the curved pipes, the sponsor has requested that we buy another entire set as a back-up set should he need replacement parts and has difficulty finding a company to manufacture identical pieces. The Operator’s manual will also be included for guidance on assembling the backdrop see Appendix L.

5.6 Changes after CDR

After Critical Design Review it was decided to continue with the original model with two exceptions. The overall frame structure was not to change. The two changes made were related to the fabric and its attachment to the frame. The first change made was the number of fabric sections that the frame was going to originally have. Instead of having five sections cut out, the number of sections increased to eight. From Figure 34, the fabric section 1 was split into three sections. An extra fabric section was added to the rear middle part of the backdrop to help conceal the step van. The second change made was the attachment of the fabric to the frame. It was planned to be attached by using Velcro attachments for the top section of the backdrop and zip ties for the base section. It was decided that the fabric would instead be attached all around using ball bungees.
Chapter 6: Manufacturing Plan

With the analysis performed on the key components, the parts needed were ordered. With companies having been contacted for quotes on raw materials and manufacturing processes, the ordering process for the parts began in mid-February with extra time for any miscommunication or lost materials. With the sponsor having approved of a $5,000 budget, negotiations on prices were attempted when ordering every part. While some components were easily available in local hardware stores, most required custom processes and ample shipping times. It was a learning experience having to purchase and fix errors when buying materials from an online source.

6.1.1 Pipes Procurement & Manufacturing

The straight aluminum pipes were procured from an online company named Buy Railings. Pipes were purchased in three different straight pipe sizes; six, eight and ten foot lengths. The rolled aluminum pipes for the curved sections of the overhand assembly were to be purchased from Chicago Metal Rolled Products (CMRP). The rolled pipes were ordered from CMRP due to the lack of appropriate equipment at Cal Poly. After receiving an initial quote from CMRP, a small adjustment was made to the rolled pipe dimensions. Tangent ends were added to each end of the rolled pipe. After this revision, a new quote was received from CMRP that was only marginally higher than the original quote, as expected. However, as a team we did not double check the final quote that CMRP provided and failed to notice that they reduced the quantity from eight pipes to one pipe. This lead to us receiving seven less pipes than we expected, and three less pipes than we needed to move ahead with the frame’s construction.

At this point the manufacturing process was delayed a few days and the team decided to contact another company to purchase the remaining rolled pipes needed. Unfortunately, the new company, Tube-Tec Bending, took longer than scheduled to complete and ship the rolled pipes. This set back the manufacturing process even further back, delaying the project by two to three weeks.

Figure 36. Straight pipes ready for manufacturing
Once the straight aluminum pipes arrived the cutting process for the straight pipes began. The aluminum pipes were cut to the proper length needed using a horizontal band saw and a chop saw. The lengths were measured based on the SOLIDWORKS model and the dimensions of the stage that Opera San Luis Obispo planned on using. Figure 38 below shows the horizontal band saw used during the manufacturing process to cut the straight aluminum pipes down to the required lengths. The saw is located at one of the Cal Poly Mechanical department machine shops. The horizontal band saw was easy to use, and it sped up the cutting process. Figure 39 shows the aluminum straight pipes after cutting them to size.
After all the cutting process was completed on the straight pipes and the rolled pipes finally arrived, a few selected pipes needed holes to be drilled. Four of the straight aluminum pipes had two holes drilled into them by using a vertical milling machine located at Mustang 60, another Cal Poly machine shop. Every hole at the pipe ends was milled carefully for a more accurate fitting during assembly. The vertical mill allowed us to have great accuracy by using the digital readout implemented into the machine. The holes had to be accurate on the pipes in order to have a perfect alignment with the endplates as shown in Figure 43 below. All four of the rolled pipes had one hole drilled also by using the mill. Figure 40 shows the hole drilling process on both the straight and rolled aluminum pipes as well as the digital readout used to have better accuracy for the hole drilling.

Figure 39. Straight aluminum pipes cut to size needed for each section

Figure 40. Drilling holes into the straight and rolled pipes.
6.1.2 Brackets Procurement & Manufacturing

The brackets needed for the endplates were purchased from GA Steel. A total of four endplates were purchased. Using SOLIDWORKS, the shape and size of the endplates were determined and designed. The endplates were cut using the high pressure water jet cutting machine seen below in Figure 41. The machine shop that houses the water jet machine works on a first come first serve basis, and after seven visits in two weeks the cutting was finally done. The holes on the end plates were also cut with the water jet; the final cutting results can be seen in Figure 42. These holes needed to match the holes drilled into both the straight and rolled aluminum pipes to ensure the endplates could be assembled with ease, as seen in Figure 43. A second bracket was designed to be made from three-inch angle iron that would be attached to the step van. The second bracket was not manufactured due to not having the step van on time. These brackets will be considered and implemented to the design once the step van is purchased. These brackets will help to attach a set of arms between the backdrop frame and the step van for better stability.

Figure 41. Water jet cutting of the endplates
Figure 42. Final results of the endplates after water jet cutting

Figure 43. Assembly of the endplates and pipes after having holes precisely drilled
6.1.3 Fabric Procurement & Manufacturing

A 30’ x 30’ vinyl-coated polyester tarp was purchased from My Tarp. During the call with a sales representative, it was learned that a lead time of 15-20 business days was required to allow for the fabric to be shipped. It was noted that this time frame did not include shipping time. During the time that the fabric took to arrive, templates of each section of the frame were made using a cheaper tarp purchased at Home Depot. The templates were made by setting up the backdrop frame and attaching the cheap tarp to every frame section with clamps and tape. Once the tarp was securely tight to the section the template was traced out. Three inches were added to the trace line, where an inch and three-quarters were required for the stitching. The remaining extra length was to give extra space to work with when the final fabric shape was cut out. Once the templates were cut out, it was used to trace and cut out the final shape from the vinyl-coated polyester tarp. After the actual fabric was cut out, it was attached to the corresponding section and checked that it fitted before sewing the edges. The hemming was done by Mitch’s Stitches, a local car upholstery shop. The final step of completing the fabric was to install grommets to every fabric section. A grommet kit was purchased online, which was simple to use. To apply the grommets onto the fabric, holes were first punched manually with a hammer and a cutting tool. The grommets were installed with even spacing around each fabric section. The curved fabric sections required more attachment points to ensure proper tension could be achieved over the complex shape.

Figure 44. Left: Template using the cheap tarp, middle: tracing the template from one of the frame sections, right: tracing the template of the top sections
6.1.4 Connectors/Hardware

All the connectors needed to put the pipes together were purchased from Buy Railings. The required connectors included 16 tee joints, four 90 degree elbows, four three-way elbows, eight adjustable connectors and four couplers. Under the “Speed Rail” Fittings model, these connectors are made of aluminum-magnesium alloy 535. Each connector came with a set screw. These parts were received together with the straight aluminum pipes. The hardware used to fasten the pipes to the endplates were procured from Home Depot. This includes 12 bolts, nuts, and washers to properly secure the endplates.
6.2 Assembly

The backdrop has four main states of assembly: completely broken down into individual components, completely assembled with the overhang collapsed, assembled into two halves with the overhang collapsed, and completely assembled with the overhang deployed. Three sets of instructions will be included that will detail how to convert each of the first three assembly states into the final fully assembled and deployed assembly state.

The first assembly of the backdrop took place in an open area on a flat level ground behind Mustang 60, one of the machine shops. The components were first placed out and organized based on their type: pipes, connectors, brackets, fabric and hardware. The necessary tools were also gathered and set aside to be used during the assembly process. These tools include two sets (one for each backdrop assembler) of the following: 3/8” drive ratchet, 9/16” wrench, 9/16” socket, and 1/4” Allen socket. The included assembly manual was used to follow detail steps of the assembly process. Each step was accompanied with a drawing of the backdrop’s current state and also included a detailed code system. The code specified every pipe and connector, each component was stamped with an alphanumeric punch set to follow the steps with ease. The clarity of the assembly manual was tested on volunteers that have no experience with the project. Safety of construction site was the most critical metric, followed by assembly accuracy and then speed.

To aid in the assembly process, component materials have been chosen to be as light as possible while still structurally sound. This reduced the chance of injury occurring while loading and/or unloading the backdrop from the truck and during the overhang deployment process.

Construction of the base assembly was only necessary the first time. The base assembly will fit into the truck without being further broken down. This step has not been tested due to not having the truck on time. However, if more space is desired in the truck, the base assembly can be split into two sections through removal of the center pipes. The two halves can then be nested within each other to create the smallest footprint possible. If needed, however, the entire backdrop can be broken down into its individual components with the use of the previously listed basic hand tools.
Deployment of the overhang assembly required the work of two individuals. With the overhang collapsed, the top fabric section was first attached to the upper arch tube. Each assembler then inserted a lift arm into the appropriate tee connector on the first arch tube. The two assemblers simultaneously pushed the arch up until the lift arms were inserted into the tee connectors located on the second arch tube. At this point the top fabric section and the middle fabric section were attached to the second arch tube. Two additional lift arms were then inserted into another set of tee connectors on the second arch, which will was then pushed up into position in the same manner as the first, with the push arms inserting into tee connectors located on the base assembly. The middle fabric section was then attached to the base assembly. Two operator’s manuals are available in Appendices I and J. Appendix I provides instructions on how to assemble the frame and attach the fabrics. Appendix J provides instructions on how to store the frame into the truck by performing a minimal amount of disassembly.

Chapter 7: Design Verification Plan

In order to justify our design and perform a full analysis, 10 tests have been performed as shown in Appendix K. These tests focused on the integrity of the pipes, connectors, and the fabric. Appendix L also shows the test procedures done during the testing period.

7.1 Pipe and Endplate Buckling Calculations

The initial tests performed were a pair of manual calculations. The first calculation was to determine whether the vertical base pipes would buckle under the load of the overhang assembly. By referring to Shigley's Mechanical Engineering Design, Tenth Edition, a safety factor of 117 resulted. Given that an acceptable success criteria is satisfied with no visual deflection or buckling, the 0.109 inch pipe wall thickness was sufficient. The next calculation aimed to determine the necessary endplate thickness. Assuming a wall thickness of 0.25 inch, a safety factor of 88 far exceeded the minimum safety factor of 5 for a satisfactory result. Based on the excessively high safety factor values, it can be determined that buckling will not be an issue in the pipes or endplates. These calculations are available in Figures E-2 and E-4 of Appendix E.

7.2 Manufacturing Feasibility Test

The next test performed was a structural prototype, with the goal of attaining valuable manufacturing information which could be taken advantage of during the manufacturing stage. From this activity, we gained firsthand experience to convince us that certain manufacturing processes would certainly have to be outsourced to professionals. Due to the curvature of the pipe, the drill bit would tend to deviate from the curved surface and producing concentric holes, perpendicular to the surface was difficult to replicate. As for the endplates, these components seemed more manageable, but due to the criticality of the component, it is also best that these parts be outsourced for a higher quality and accuracy.

7.3 Sound Testing

Aside from analyzing the structure aspect of the backdrop frame, the sound reflectivity aspect
was a high priority for the team and the project sponsor. Researching existing acoustically reflective panels, many were manufactured using plywood or costly multi-layered fabrics that were not suitable for long-term outdoor exposure. In our research, we did identify a fabric called the “Lunar Duo”, manufactured by Gerriets. This fabric is 100% polyester and is claimed to have a sound reflectance of 90%. As a result, we decided to make a compromise between sound reflectance and material durability. We ordered a sample of a polyester coated vinyl tarp and performed our test on this material.

When performing this test, a sound-controlled environment where external noise sources will not disrupt the recording is required. This test will require a sample fabric material, microphone, an amplifier, synthesizer, looping pedal, computer, and recording software. No special safety equipment required, however, be mindful of tripping hazards caused by wiring to amplifier, synthesizer, looping pedal, microphone, computer and recording hardware. Also, avoid loud test signals to reduce risk of hearing damage.

The sound test was performed to capture the relative sound reflectivity of the backdrop fabric compared to plywood, the industry standard. The sound level in decibels was recorded, from which sound intensity can be calculated and compared. The experiment was set up by fixing a 2’x2’ square of material in a vertical orientation. A Shure SM57 microphone was placed 3” from the material with the microphone pointing towards the material. An amplifier was placed 15” from the material, with the speaker in the amplifier pointing towards the material as shown in Figure 48.

A synthesizer was connected to a looper pedal that connects to the amplifier. We then began a loop on the looper pedal, and recorded a C-chord on the synthesizer. The loop on the looper pedal was then ended and the loop was ran on repeat. The recording software, PreSonus Studio One, was started with a peak meter to capture the maximum decibels of each sound loop. Figure 49
demonstrates the software aspect of the test set-up, with the PreSonus AudioBox 44VSL utilized as an audio interface between the synthesizer and the software.

Figure 49. Sound testing using the program PreSonus AudioBox 44VSL

Twenty loops were recorded with the polyester coated vinyl sample and then replaced with plywood and polyester canvas to compare the sound reflection properties. Once the sound tests for both the polyester canvas and polyester coated vinyl were completed, the results were compared to the test on plywood. Given that plywood has a sound reflectance of 96% per the website performancepanels.com, using plywood as our datum is a reasonable assumption to base the data from. By comparing to plywood, the polyester canvas reflected 52% of the sound energy, while the polyester coated vinyl reflected 65%. As a result, the decision was made to proceed with the polyester coated vinyl. Although 65% sound reflectance may seem like a relatively small value, it is worth noting that Gerriets’ Clivia Echo stage Velour product is designed as a sound reflective material. However, it is claimed to have a sound reflectance of up to 80% while being unsuitable for outdoor conditions. It does not protect against UV-radiation and is not water-proof. On the other hand, the vinyl coated polyester is UV-resistant, waterproof, and tear-resistant. As a result, it was agreed upon that the slightly inferior sound reflectance was a necessary decision in order to both maximize the sound projection performance and the durability of the material.

During this test, there were some difficulties which might have influenced the accuracy of this testing. One of the greater test design concerns was how large of a sample would be required and how far from the fabric should the recording microphone be located for accurate results. We utilized a 2’x2’ sample we purchased and did not use the next available size of 5’x5’ due to costs. However, it would be recommended that a sample as large as possible is used, so that the reflected sound is from the intended material. However, we justify that the 2’x2’ fabric would be suffice for accurate results given that the view factor of the microphone and sample material at 3” apart is high.
7.4 FEA Studies

The next two tests were simulations performed on one hoop of the overhang assembly and on the entire system. The first simulation was performed on a standalone pivoting hoop, where a 200 lbf load was applied down on the center of the straight pipe. This study predicts that a deflection of 1.28 inches would result. Comparing this study to that where the entire structure was considered in the analysis, the results were similar. With a 10 lbf transverse load at each end of the straight pivoting hoops, and a 40 lbf weight representing the weight of the tarp, a 0.38 inch deflection was predicted. For comparison, the first simulation under a 60 lbf load would correspond to a deflection of 0.384 inch. As a result, it is recommended that loading is limited to 35 lbf as the deflection of the beam should be kept below 0.25 inches to prevent permanent deformation.

7.5 Setscrew Test: Bending

The following two tests were performed to examine the effect that loading has on the pipes and connectors, given that there is a 0.1-inch clearance. For the first test, a straight connector, a two ft pipe, an eight ft pipe, a vise, two V-blocks, two blocks of wood, and calipers were required. This test was performed to determine the effect that the bending of a pipe would have on the setscrews of its connectors. This test was performed in Cal Poly's Mustang 60 Machine Shop. For safety purposes, close-toed shoes and safety glasses are required to replicate this test. Setting up the experiment was one of the greater challenges, as it was a safety concern to securely fixing one end of the pipe. As a result, force was applied on the pipe manually to identify any possible slip of the pipe prior to loading with higher weight. Figure 50 illustrates the fixing of the pipe on one end using a vise and other components.
The experiment was set-up with the two ft pipe being fixed on one end to a vise using V-blocks and wooden blocks below the pipe to provide support for the V-blocks. The pipe also shared a straight connector with the eight ft pipe on the other end where the loading was applied. With the connector rigidly fixed, a mark was made on the setscrews so that they serve as a reference when measuring their angular deviation after loading. We then loaded 16.2 lbf weights on the pipe at a distance of 5.5 ft and measured the corresponding pipe deflection and setscrew deviation. The deformed pipe under loading is shown in Figure 51 and the resulting data is tabulated in Table 9 below.
As can be seen from the data in Table 11, the pipe deflection and setscrew rotation were not linearly proportional to the loading applied. There was a weight between the 16.2 and 32.4 lbf loads applied where the setscrew began to slip. While it is reasonable that the setscrew rotation was non-linear, the deflection being non-linear could be attributed to the difficulty we had for this test and the torsion test which will be discussed next.

Table 11. Weight deflection on aluminum pipe

<table>
<thead>
<tr>
<th>Weight [lbf]</th>
<th>Pipe Deflection [in]</th>
<th>Setscrew Angular Deviation [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.2</td>
<td>0.78</td>
<td>0.0</td>
</tr>
<tr>
<td>32.4</td>
<td>3.36</td>
<td>3.5</td>
</tr>
</tbody>
</table>

An uncertainty calculation was performed for this test, with the calculations shown in Appendix L. The resulting pipe deflection when 16.2 lbf was applied is 8.75E-03 ± 2.79E-05 inch per lbf-ft of torque applied.

7.6 Setscrew Test: Torsion

The second setscrew test has an identical set-up as the previously discussed test, with the exception that the pipe was subjected to torsion. This test was performed to simulate the effect of a torque on the connectors rather than a bending moment. A tee-connector was required for this test, and a two ft lever arm was used to apply the torque. The fixture of the pipes and the loading are illustrated on Figure 52.
From the bending and torsion tests, the setscrews were more sensitive to applied torques. As a result, a shorter lever arm was utilized in order to identify the max loading condition. We proceeded with the test by placing one of the 16.2 lbf weights one at a time and recording the corresponding setscrew angular deflection. This data is tabulated in Table 12.

Table 12. Angular deflection caused by torsion

<table>
<thead>
<tr>
<th>Weight [lbf]</th>
<th>Setscrew Angular Deviation [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.2</td>
<td>0.0</td>
</tr>
<tr>
<td>32.4</td>
<td>0.5</td>
</tr>
<tr>
<td>48.6</td>
<td>3.3</td>
</tr>
<tr>
<td>64.8</td>
<td>6.8</td>
</tr>
</tbody>
</table>

As can be seen from setscrew deviation is not which the setscrew begins to increases at an increasing rate as further weight is added. The maximum setscrew rotation during this test was 6.8° from a torque of 129.6 lbf-ft. Although this slip would be significant, it should be noted that this would occur when a pipe perpendicular to a tee-connector is free to rotate. Once fully assembled, all the pipes will have both their ends in a connector and a torque of the magnitude
discussed above is highly unlikely.

7.7 Assembly for Extended Periods of Time Testing

The final test was performed to determine the reaction of the fully assembled structure when left to react to its surroundings for at least 24 hours. With the assembly fully deployed and the fabric panels attached, 10 key connectors had their setscrews marked to serve as datums for any rotation of the setscrews. With the structure being subjected to wind loads as will be the case in its actual operation, the backdrop remained un-manipulated with for approximately 30 hours. Since the setscrews were tightened tightly prior to testing, all of the setscrews remained in their original position. Thus, the safety concern of the setscrews loosening is of low priority. This concern may increase in priority as the setscrews wear out, and therefore, the setscrews should be inspected in order to reduce the risk of setscrew error.

Chapter 8: Project Management

This section covers how the team approached and completed the design and construction of the backdrop. It includes key deliverables that guided the completion of the project. This section also includes key activities that were prioritized due to their high impact on the project’s overall success.

8.1 Overall design process

The strategy the team adopted was an organized and systematic approach. Prior to beginning the ideation process and performing any sort of analysis, approximately three weeks were spent clarifying the scope of the project presented. Creating a proper foundation built on an accurate understanding of the final product expectations is key to the success of any project. The next phase in the project began with brainstorming ideas to solve the established issues. After considering several feasible designs, the construction of concept prototypes followed. These models served the purpose of exploring different designs, while exposing us to possible difficulties we might have encountered with the construction of the final product. Failure Modes and Effects Analysis (FMEA) were then performed on the prototypes. The focus of this process was to determine ways in which the design might fail to perform its intended function. In addition, the cause of these failures and their effect on the customer in terms of costs, safety, etc. are considered. Following the prototyping and FMEA stages, the Preliminary Design Review (PDR) ensued. The key deliverables for the PDR included a report and a presentation on our progress status. The PDR report served as documentation of our design concepts and their supporting evidence. The remainder of the quarter was then reserved for design analysis. These phases occupied the first of three quarters that were allocated towards the success of the project.

The second quarter of the project commenced with a key deliverable due by the second week. The Interim Design Review (IDR) will consist of a class presentation, without the report.
By this stage of the design process, we established all and any key decisions that remained open upon concluding the PDR. Subsequently, structural prototyping allowed our team to create a functional prototype in order to determine the assembly of the product and if components could be manufactured. Our next stage was the Critical Design Review (CDR). This process focused on presenting the analysis for the final design choice. Once the final design was established, risk assessments were performed to identify risks and plans to manage them. Our second quarter concluded with a manufacturing and test review. During this review, we demonstrated the status of our manufacturing and provided information regarding testing plans.

The third and final quarter of the project resumed the manufacturing phase of the project. The bulk of the third quarter was allocated to the manufacturing of the final design, and also the testing for safety and proper functionality. An operator’s manual was written to fully document the proper method of operation of the finished product. During the final stages of the project, we began preparations for the final design review and the project exposition. Our design team managed and monitored our progress through the use of a Gantt chart, as shown in Appendix M. The Gantt chart allowed us to assign tasks to individual team members and easily stay up to date on overall project progress.

8.2 Key Activities

One of the key activities during this project was preparing for the Manufacturing and Test Review. This included beginning to order the parts necessary for the manufacturing stage. Simultaneously, some of the planned testing in the DVP was performed. The main testing that we plan on pertains to the sound projection of the vinyl-coated polyester fabric. For the audio tests, various material samples were used for the purpose of testing against one another. Another test we performed was to test the strength of the connectors and their setscrews used throughout the structure. The failure of any one of these joints could lead to the collapse of the backdrop. A sample of test connectors and pipes were procured to determine their holding capacity. The expected mode of failure proved to be correct: between the set screw and the tube which the connector was holding. When loaded with a lateral force, the tubes bent and began to pull out of the connector. When loaded with a torsion, the set screw began to slip, allowing the tube to rotate. These tests were key activities as we prepared to build the final prototype.

8.3 Plan Deviations

Another key activity during the final stages of the project was the completion of the aluminum frame of the backdrop. The frame needed to be completed and finalized before design of the fabric could begin. However, this milestone was delayed by the procurement of the rolled pipes. A new company had to be sourced to make the pipes, causing a three-week delay. This pushed back the design and manufacturing of the fabric sections of the backdrop to a much later date than anticipated, forcing this process to be completed in a much shorter time than originally planned. This short time period meant that we no longer could outsource the custom fabric manufacturing to an outside company, as the turn-around time for such a project would have been at least three weeks. Deciding to create the fabric templates ourselves saved the time lost by the rolled pipe set back.
8.4 Key Deliverables

Table 13. Key deliverables broken down by quarter

<table>
<thead>
<tr>
<th>Quarter 1</th>
<th>Quarter 2</th>
<th>Quarter 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statement of Work</td>
<td>Interim Design Review</td>
<td>Hardware/Safety Demo</td>
</tr>
<tr>
<td>Preliminary Design Review</td>
<td>Critical Design Review</td>
<td>Final Design Review</td>
</tr>
<tr>
<td>Manufacturing &amp; Test Review</td>
<td>Expo</td>
<td></td>
</tr>
</tbody>
</table>

Table 9, shown above, displays the key deliverables that guided our progress over the course of the design project. Figure 53 below illustrates the complete setup of the backdrop presented during the 2018 senior design EXPO.

Chapter 9: Conclusion

This document identifies and explains the project’s scope, proposed design concept, final design and delivered product. The project’s scope was established based on information from Mr. Brian Alhadeff gathered during his presentation at Cal Poly and through additional questioning. The proposed design was selected using several ideation methods that balanced the influences of multiple factors, such as usability, manufacturing feasibility, cost and aesthetics. Once the design concept was approved by Mr. Alhadeff, we continued forward by procuring components. With parts in hand, we were able to manufacture the desired product and conduct tests along the way. At senior project expo, we successfully presented and demonstrated the finished backdrop to Mr. Alhadeff and his team. Moving forward, we will continue to be available to Mr. Alhadeff to answer any questions about operation, modification, or reproduction of the product.

9.1 Future Development Suggestions

With the final product manufactured and assembled we are still open for suggestions to improve the quality and performance of the backdrop. The final product had a few small gaps between the frame and the fabric allowing the sunlight to pass through in a few different locations. The aluminum pipe frame is also visible to the public, but an all-black background might be desired. To fix these potential problems, one suggestion for Opera San Luis Obispo is to apply Velcro strips along the edges of the fabric and to then attach some form of covering strips along the openings, thus concealing the aluminum pipes and the gaps.

We also suggest the procurement of large water barrels to attach to the endplates and anchor the backdrop for additional safety. This would be in addition to braces that connect the backdrop to the support truck.
9.2 Final Product Images

Figure 53. Backdrop fully deployed at Senior Project Expo 2018 with stage set at 24” height
Figure 54. The backdrop in storage mode with the two halves nested together

Figure 55. Start of the deployment procedure: Halves separated then connected with four center pipes
Figure 56. Stage one of deployment with the first two push arms installed into position

Figure 57. Backdrop fully deployed with final two push arms installed (stage not shown)
Figure 58. Backdrop fully deployed (stage not shown)
Figure 59. View of the upper fabric panels from inside the backdrop

Figure 60. Rear view of the backdrop fully deployed
Figure 61. Rear of the backdrop after it has been collapsed down to prepare for transport
References


Appendix A: Interview Notes

Mobile Opera Backdrop Questions

1) Truck/Van update (Type, Dimensions if possible)
   a) We can also help with some research on possible trucks/vans
      i) What’s on your mind, size wise?
         ● There are two main options I’m interested in… (1) a 22-foot Fed-ex / UPS step van that
           would be donated by that organization – basically the largest/longest variety. The other
           option would be the largest or “extended” Mercedes/Dodge sprinter van. I do not have
           the exact dimensions available but I think you might be able to look those sizes up easily
           enough.

2) Will the backdrop be the only set of equipment transported on the truck/van?
   ● No. Not at all… The van will also carry the stage, audio amplification equipment,
     lighting, full sized electric keyboard, any staging props and or set pieces. Even with all of
     this stuff the van will still have plenty of room for other things too. When it’s not being
     used as a “mobile opera house” the van may also be used for moving tasks.

3) What is the dimension for the total stage area (width, length, height)?
   ● Here is a great video of the stage we are thinking of but I think this video describes a
     stage that is about ½ the size I’m interested in… https://youtu.be/aslhLpdVpaI I am
     looking at a stage right now that would be about 16-feet by 16-feet or at minimum 8-feet
     by 16-feet. We would like the stage to be at minimum 32 inches high.

4) Time estimated for the backdrop to be assemble?
   ● Less than 1 hour.

5) A 2 men setup?
   ● Yes

6) Specific theme or simply a plain black backdrop?
   ● Generally speaking we would like this to be black, however in my phone call with Juan,
     we talked about using the perforated “tool wall” material – this is the material one would
     see in a garage where you can stick different braces to hold tools. Likewise, while our
     use would not be for holding tools, using this kind of material would allow the opera to hang
     endless possibilities: backdrops, small set pieces, a projection screen, etc… I’ve attached
     two photos below of that surface type.

7) Will the backdrop be mounted into the stage or from the ground?
   ● I believe we want this mounted to the ground so that any movement on the stage will not
     interfere or move the backdrop.

8) Maximum height for the backdrop?
   ● I’m thinking that since we already know the stage will be about 32 inches from the
     ground, and that we need the stage to be about 3-4 feet above a standing performer, and
     the stage needs to fit in a 22-foot long truck… Hmmm… Maybe no higher than 16 feet?

9) Since the backdrop will have a shell-like shape, would you like it to cover-up the
    entire sides of the stage or just partial?
   ● I think the backdrop should cover about 3-4 feet of the stage offering a sort of half-shell
     appearance.
Figure B-1. This QFD chart displays the customer requirements of the customer and compares them to various engineering specifications. The weighted importance of these specifications are then calculated to better focus our design process. Current Wenger products are also rated based on the customer requirements, giving us additional goals that our team needs to exceed.
## Appendix C: Benchmarking and Preliminary Analyses

Table C-1. Benchmark of Current Acoustic Shell Devices

<table>
<thead>
<tr>
<th></th>
<th>Inflatable Shell</th>
<th>Showmobile</th>
<th>Legacy Panels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assembly</strong></td>
<td>Uses a silent motor to inflate the shell in under 10 minutes</td>
<td>Uses battery powered hydraulics to open up the stage area</td>
<td>Each panel can be assembled by one person in 1 to 2 minutes</td>
</tr>
<tr>
<td><strong>Aesthetic</strong></td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Storage space</strong></td>
<td>Can be stored in a 5-ft diameter bag</td>
<td>Converts in a trailer</td>
<td>Fold up to take less storage space</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>Vinyl-coated nylon</td>
<td>undisclosed</td>
<td>ABS</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$2300</td>
<td>$1700 (used)</td>
<td>$1700</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>To large, smallest size comes in 24-ft wide</td>
<td>Stage area to small</td>
<td>One panel is not enough, need at least 12-15 panels</td>
</tr>
</tbody>
</table>

Table C-1 displays three available acoustic shells and compares their properties based on several different factors. Our backdrop will combine performance, aesthetics, and affordability to better fulfill each of these requirements.
Appendix D: Pugh Matrices and Weighted Decision Matrix

<table>
<thead>
<tr>
<th>concept</th>
<th>Canvas</th>
<th>Plastic/Plexiglass</th>
<th>Ziptie</th>
<th>Velcro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceals Backstage Vehicle</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Projects Audio</td>
<td>-</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Stable outdoors</td>
<td>5</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Easy to deploy</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Quick to deploy</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Low Cost</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Durable</td>
<td>5</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Visually Appealing</td>
<td>5</td>
<td>-</td>
<td>5</td>
<td>+</td>
</tr>
</tbody>
</table>

- Acoustic material matrix uses vinyl as the reference.
- While the acoustic material attachment method uses grommets with cord as reference.

Figure D-1: This Pugh matrix shows the point scale on how each function was compared to vinyl.
Figure D-2. This Pugh Matrix compares and evaluates different methods of hanging a pegboard from the backdrop.
Figure D-3. This Weighted Decision Matrix compares various configurations of the backdrop using a variety of different materials and attachment methods.
Figure E-1. FEA results showing displacement of frame. Maximum displacement (0.385") occurs at middle of top-center tube. Base was held fixed. Loads were placed to simulate gravity, lights and fabric.
From Shyncke, EX 6-13: For the top right end plate hole

Given:
\[ W = 3 \text{ in} \]
\[ d = 0.5 \text{ in} \]
\[ F_{\text{rep}} = 30 \text{ lb} \]
\[ F_{\text{prem}} = 11 \text{ lb} \]

Assume:
- Quarter Spherical Fad
\[ F_{\text{rep}} = 18 \text{ in} \]
\[ F_{\text{prem}} = 108 \text{ in} \]
\[ z = 4 \text{ in} \]
\[ F_{\text{prem}} = 1000 \text{ lb} \]
\[ F_{\text{prem}} = 50 \text{ lb} \]
\[ F_{\text{prem}} = 250 \text{ lb} \]

Solve:
Quarter spherical shell of fabric material.

Tensile Force:
\[ A = \frac{1}{3} (4 \text{ in})^2 \]
\[ = \frac{1}{3} (108 \text{ in})^2 \]
\[ = 36,441 \text{ in}^2 \]

\[ F_{\text{rep}} = 18 \frac{60}{y^2} (36,441 \text{ in}^2) \left( \frac{1 \text{ in}^2}{12 \text{ in}^2} \right) \left( \frac{1 \text{ lb}}{16 \text{ oz}} \right) = 31.9 \text{ lb} \]

\[ F = \frac{1}{4} \left( F_{\text{rep}} + F_{\text{prem}} + F_{\text{prem}} + F_{\text{prem}} + F_{\text{prem}} + 2 F_{\text{prem}} \right) \]
\[ = \frac{1}{4} \left( 30 + 11 + 31.9 + 100 + 50 + (2)(250) \right) \]
\[ = 181.16 \text{ lb} \]

From Table 1-20: For 1020 steel HR: \( S_{\text{ue}} = 55 \text{ Kpsi} \)

Eqn 6-19: \( S_e = k_a k_b k_c k_z S_e \)

Eqn 6-2: \( S_e' = 0.5 S_{\text{ue}} = (0.5)(55) = 27.5 \text{ Kpsi} \)

Surface Factor: Eqn 6-14
\[ K_a = a S_{\text{ub}}^b \]

Table 6-2: \( a = 14.4, b = -0.718 \)

\[ K_a = (14.4)(55)^{-0.718} = 0.811 \]
\[ K = \sqrt{\frac{E}{A}} = \sqrt{\frac{\frac{E}{t}}{\frac{P}{L}} (D^2 - d^2)} = \sqrt{\frac{1}{12} (D^4 - d^4)} = \left[ \frac{1}{12} \left( \frac{2.375^2 + 2.15^2}{2} \right) \right]^{1/2} \]

\[ K = 0.802 \text{ in} \]

Table 4.2:  Notation: 6061 Al : \( E = 40 \times 10^6 \text{ psi} \)

Table 4.2:  Fixed - Fixed : L = 1 \text{ (conserve)}

Table 4.2:  E = 10.4 \times 10^6 \text{ psi}

\[ \left( \frac{1}{K} \right) = \left( \frac{2\pi^2 E}{L^2} \right)^{1/2} = \left[ \frac{12\pi^2}{40,000 \times 10^6} \right]^{1/2} = 71.6 \]

\[ \frac{1}{K} = \frac{67}{0.202} = 83.54 \]

\[ \frac{1}{K} > \left( \frac{8}{K} \right) \text{ Euler Column} \]

\[ \frac{P_{cr}}{K} = \frac{Gt^2 E}{(4/K)^2} \]

\[ P_{cr} = \frac{\pi^2}{4} \left( 2.375^2 - 2.15^2 \right) \left( \frac{11(11^2)(10.9 \times 10^6)}{83.54} \right) \]

\[ P_{cr} = 11,412 \text{ lb} \]

\[ r = 11,412 \]

\[ n = \frac{11,412}{97.2} = \frac{117}{97.2} \]

Figure E-3. Hand calculations analyzing the endplate (Page 2/2).

E-3
Figure E-4. Hand calculations analyzing the buckling in the vertical tubes of the frame (Page 1/2).
Figure E-5. Hand calculations analyzing the buckling in the vertical tubes of the frame (Page 2/2).
Appendix F: Bill of Materials and Drawing Package

![Table of Bill of Materials]

Figure F-1. Bill of Materials showing the costs for each component.
Table F-1. Vendor name, cost and payment method for each group of components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Vendor</th>
<th>Cost</th>
<th>Payment Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Tubes</td>
<td>Butler Built</td>
<td>$828.00</td>
<td>Business Check</td>
</tr>
<tr>
<td>Connectors</td>
<td>BuyRailings.com</td>
<td>$1,517.72</td>
<td>Online Order</td>
</tr>
<tr>
<td>Fabric Material</td>
<td>TarpsPlus.com</td>
<td>$820.00</td>
<td>Online Order</td>
</tr>
<tr>
<td>Fabric Labor</td>
<td>SLO Sail &amp; Canvas</td>
<td>$990.00</td>
<td>Business Check</td>
</tr>
<tr>
<td>Rolled Tubes</td>
<td>Chicago Metal Rolled Products</td>
<td>$580.00</td>
<td>Online Order</td>
</tr>
<tr>
<td>Endplates</td>
<td>Metal Supermarkets</td>
<td>$220.00</td>
<td>Online Order</td>
</tr>
<tr>
<td>Hardware</td>
<td>McMaster-Carr</td>
<td>$62.04</td>
<td>Online Order</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td><strong>$5,017.76</strong></td>
<td></td>
</tr>
<tr>
<td>ITEM #</td>
<td>PART #</td>
<td>DESCRIPTION</td>
<td>QTY.</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
<td>---------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>100-A</td>
<td>BASE ASSEMBLY</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>200-A</td>
<td>OVERHANG ASSEMBLY</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>300-A</td>
<td>ENDPLATE ASSEMBLY</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>400-A</td>
<td>TRUCK BRACE ASSEMBLY</td>
<td>2</td>
</tr>
<tr>
<td>ITEM #</td>
<td>PART #</td>
<td>DESCRIPTION</td>
<td>QTY.</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>----------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>101-T</td>
<td>Rear Center Tube</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>102-T</td>
<td>Rear Outer Tube</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>103-T</td>
<td>Upper Side Tube</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>104-T</td>
<td>Lower Side Tube</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>105-T</td>
<td>Rear Vertical Tube</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>106-T</td>
<td>Front Vertical Tube</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>107-T</td>
<td>Rear Brace Tube</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>108-T</td>
<td>Side Brace Tube</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>109-C</td>
<td>Tee Connector</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>110-C</td>
<td>Elbow Connector</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>111-C</td>
<td>3-Way Elbow Connector</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>112-C</td>
<td>Angle Connector</td>
<td>8</td>
</tr>
</tbody>
</table>

ASSEMBLY IS SYMMETRICAL UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: XX.X ± .5" XXX ± .01" XXXX ± .005

MATERIAL: MULTIPLE MATERIALS

DRAWN BY: MOBILE OPERA BACKDROP

DATE: 1/30/18 SHEET 1 OF 1 SCALE: 1:32

CAL POLY
SAN LUIS OBISPO

INTERPRET DRAWING PER AIA Y1.4-2009

SIZE A
<table>
<thead>
<tr>
<th>ITEM #</th>
<th>PART #</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>201-T</td>
<td>Arch Center Tube</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>202-T</td>
<td>Arch Curved Tube</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>203-T</td>
<td>Push Arm Tube</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>204-C</td>
<td>Straight Connector</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>205-C</td>
<td>Tee Connector</td>
<td>8</td>
</tr>
</tbody>
</table>

ASSEMBLY IS SYMMETRICAL
UNLESS OTHERWISE SPECIFIED.
DIMENSIONS ARE IN INCHES.
TOLERANCES:
X ± .05
Y ± .08
Z ± .06

CAL POLY
SAN LUIS OBISPO

MATERIAL: MULTIPLE MATERIALS
TITLE: OVERHANG ASSEMBLY
DRAWN BY: MOBILE OPERA BACKDROP
DATE: 1/30/18
SHEET 1 OF 1 SCALE: 1:32
<table>
<thead>
<tr>
<th>ITEM #</th>
<th>PART #</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>301-P</td>
<td>Endplate</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>302-H</td>
<td>1/2&quot;-13 Bolt</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>303-H</td>
<td>1/2&quot;-13 Cap Nut</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>304-H</td>
<td>1/2&quot; Washer</td>
<td>12</td>
</tr>
<tr>
<td>ITEM #</td>
<td>PART #</td>
<td>DESCRIPTION</td>
<td>QTY.</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>------------------------</td>
<td>------</td>
</tr>
<tr>
<td>-</td>
<td>400-A</td>
<td>Truck Brace Assembly</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>401-T</td>
<td>Truck Brace Tube</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>402-C</td>
<td>Tee Connector</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>403-P</td>
<td>Truck Bracket</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>404-H</td>
<td>1/2'-13 Bolt</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>405-H</td>
<td>1/2'-13 Nut</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>406-H</td>
<td>1/2' Washer</td>
<td>2</td>
</tr>
<tr>
<td>PART #</td>
<td>DESCRIPTION</td>
<td>QTY.</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>201-T</td>
<td>ARCH CENTER TUBE</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Cal Poly**
**San Luis Obispo**

**MATERIAL:** 6061-T6 ALUMINUM

**DRAWN BY:** MOBILE OPERA BACKDROP

**DATE:** 1/30/18

**SCALE:** 1:1

F-16
<table>
<thead>
<tr>
<th>PART #</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>203-T</td>
<td>PUSH ARM TUBE</td>
<td>4</td>
</tr>
</tbody>
</table>

**CAL POLY**
SAN LUIS OBISPO

MATERIAL: 6061-T6 ALUMINUM

DRAWN BY: MOBILE OPERA BACKDROP

DATE: 1/30/18

SCALE: 1:1

F-18
PART # | DESCRIPTION | QTY.
--- | --- | ---
401-T | TRUCK BRACE TUBE | 2
<table>
<thead>
<tr>
<th>PART #</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>403-P</td>
<td>TRUCK BRACKET</td>
<td>2</td>
</tr>
</tbody>
</table>

CAL POLY
SAN LUIS OBISPO

MATERIAL: 1020 STEEL
TITLE: TRUCK BRACKET
DRAWN BY: MOBILE OPERA BACKDROP
DATE: 1/30/18
SCALE: 1:2

F-21
Appendix G: Design Hazard Checklist and FMEA

DESIGN HAZARD CHECKLIST

Team: Mobile Opera Backdrop
Advisor: Professor Harding
Date: 11/09/17

Y  N
1. Will the system include hazardous revolving, running, rolling, or mixing actions?
2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
3. Will any part of the design undergo high accelerations/decelerations?
4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
5. Could the system produce a projectile?
6. Could the system fall (due to gravity), creating injury?
7. Will a user be exposed to overhanging weights as part of the design?
8. Will the system have any burrs, sharp edges, shear points, or pinch points?
9. Will any part of the electrical systems not be grounded?
10. Will there be any large batteries (over 30 V)?
11. Will there be any exposed electrical connections in the system (over 40 V)?
12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
16. Could the system generate high levels (>90 dBA) of noise?
17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
18. Is it possible for the system to be used in an unsafe manner?
19. For powered systems, is there an emergency stop button?
20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any “Y” responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Figure G-1. Questions asked in the Design Hazards Checklist.
<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>3) Should the assemblers lose their grip of the pivoting hoops, the hoops will freely rotate.</td>
<td>The overhang assembly was divided into two 30 degree rotations, eliminating the need for assemblers to exert themselves to prevent the hoops from pivoting forward. This is due to the fact that the center of gravity of the two hoops combined offsets the fact that the front hoop passes the 90 degree threshold.</td>
<td>11/14/18</td>
<td>11/14/18</td>
</tr>
<tr>
<td>4) The frame will consist of two U-shaped aluminum pipes which will pivot overhead. The performers will be underneath the shell created by these pipes weighing approximately 30 lb each.</td>
<td>There will be connector bars between these pivoting pipes in order to keep them in fixed positions.</td>
<td>11/14/18</td>
<td>11/14/18</td>
</tr>
<tr>
<td>5) There are two possible projectiles. The first being connector bars between the pivoting pipes which will fix them into their final assembly positions. If the pivoting pipes were to rotate in opposite directions, they could disconnect and the connectors could become projectiles. Other possible projectiles are accessories such as lighting and decorations the user intends to hang from the pivoting pipes.</td>
<td>In order to securely keep the connector bars attached to the pivoting pipes, T elbow joints will be utilized and tightened for secure fixtures.</td>
<td>11/14/18</td>
<td>11/14/18</td>
</tr>
<tr>
<td>6) As mentioned in Hazard #5, if gravity were to force the pivoting pipes to rotate in opposing directions, they could detach from the connector bars and collapse.</td>
<td>In order to securely keep the connector bars attached to the pivoting pipes, T elbow joints will be utilized and tightened for secure fixtures.</td>
<td>11/14/18</td>
<td>11/14/18</td>
</tr>
<tr>
<td>7) The sponsor expects the design to include hanging pegboards, to which he will be able to hang other objects.</td>
<td>FEA analysis determined that approximately 50 lbf loading would be the maximum loading capacity.</td>
<td>11/14/18</td>
<td>01/28/18</td>
</tr>
</tbody>
</table>

Figure G-2. Description of hazards and the suggested preventative action to the Design Hazards Checklist questions.
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>12) The pivoting pipes will store a considerable amount of energy, which can cause severe damage if they were to strike a person. They currently have a pivoting radius of about 12 ft and weigh 25 lb.</td>
<td>T-elbow joints will be used to store that energy in the pipes.</td>
</tr>
<tr>
<td>17) The product will be exposed to several outdoor conditions and will need to withstand winds of 30 mph</td>
<td>The frame will be fixed to the side of the van via bolted extension arms to combat higher speed winds.</td>
</tr>
<tr>
<td>18) Injury can be caused if appropriate precautions are not taken to safely assemble the system.</td>
<td>Safety precautions will be provided in a manual regarding assembly procedures and load limits.</td>
</tr>
</tbody>
</table>

Figure G-2. Continued
<table>
<thead>
<tr>
<th>System / Function</th>
<th>Potential Failure Mode</th>
<th>Potential Effects of the Failure Mode</th>
<th>Potential Causes of the Failure Mode</th>
<th>Current Preventative Activities</th>
<th>Recommended Action(s)</th>
<th>Responsibility &amp; Target Completion Date</th>
<th>Actions Taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base level support platform system</td>
<td>Gap between building and stage</td>
<td>Platform fails - gap</td>
<td>2. Backlevel: Geometric error around stage dimensions</td>
<td>2. Testing</td>
<td>1x12</td>
<td>Confer stage dimensions with sponsor</td>
<td>Robby (12/3/18)</td>
</tr>
<tr>
<td>Base level support platform system</td>
<td>Difficulty moving stage</td>
<td>1. Structural error: Frame not parallel to 2. Outdoor damage</td>
<td>6. Scheduling delays</td>
<td>2. Testing</td>
<td>2x18</td>
<td>Work with sponsor to confirm necessary dimensions for performance and equipment, perform appropriate testing</td>
<td>Robby (12/3/18)</td>
</tr>
<tr>
<td>Pixel support projection system</td>
<td>Projections systems inactive</td>
<td>Pixel failure - projection systems fail</td>
<td>3. Pixel failure: Defect in manufacturing process</td>
<td>5. Testing</td>
<td>3x12</td>
<td>Conduct pixel analysis, run FEA analysis, research pixel design changes, etc.</td>
<td>Kevin (12/3/18)</td>
</tr>
<tr>
<td>Performance stability and describe performance toward audience</td>
<td>Does not project stage audio</td>
<td>Performance cannot be heard by audience</td>
<td>3. Performance not projected to appropriate location</td>
<td>3. Testing</td>
<td>3x12</td>
<td>Conduct performance to appropriate location</td>
<td>Juan (12/3/18)</td>
</tr>
<tr>
<td>General / Connect assembled</td>
<td>The stability may be compromised</td>
<td>Backdrop fails - collapse</td>
<td>10. The effect of using connections increases</td>
<td>6. Testing</td>
<td>2x18</td>
<td>Purchase a variety of connectors and fasteners for testing</td>
<td>Robby (12/3/18)</td>
</tr>
</tbody>
</table>

Figure G-3. FMEA table with the preventative action results to the possible failure modes.
Appendix H: Specification Sheets

Figure H-1. Aluminum pipe specifications (Schedule 40 pipe shown).
Figure H-2. Chemical composition and physical properties of connectors.
Certificate of Compliance

The Hollaender Mfg. Co. hereby certifies that the products listed below meet or exceed all requirements of the following specifications:

**Product:** Speed-Rail®, Nu-Rail® and Cast Internia-Rail® fittings as manufactured by The Hollaender Mfg. Co.

**Metal:** Fittings cast of aluminum alloy 535
- Aluminum ingot complies to ASTM B179
- Product cast in accordance with ASTM B26

**Special Note:** We certify that there are no traces of mercury in this alloy, per the attached standard report and alloy chemical analysis.

**Set Screw:** Forged internal/external knurl cup point set screw with class 3A threads complies with ANSI/ASME B18.3 & FF-S-200A

**Standard Screw:** Complies with ASTM F912 and plated per ASTM B633 followed by trivalent conversion & JS 600 topcoat. Minimum coating thickness 8 micrometers measured per ASTM B487.

**Optional Screw:** Stainless Steel 302 alloy set screw complies with ASTM F880

**Testing:** Structural tests have been performed on Hollaender handrail systems and individual components by certified independent laboratories including Space Dynamics Research Corp., Belcan, Pittsburgh Testing Laboratories and University of Dayton Research Institute.

**Design:** Hollaender Structural Fittings, when properly installed per manufacturer recommendations, meets or exceed all applicable requirements as specified by Code of Federal Regulations 1910.23 (OSHA), IBC, BOCA, UBC and SBC.

All products supplied by the Hollaender Mfg. Co. are manufactured completely in the United States of America.

Figure H-3. Certification that connectors meet or exceed federal regulations.
December 3, 1975

Mr. Ralph W. McMickle
Senior Structures Engineer
Ford, Bacon & Davis Construction Corporation
P.O. Box 1782
Monroe, Louisiana 71201

Dear Mr. McMickle:

This is in response to your letter of April 23, 1975, addressed to Mr. Jim Powell, Area Director, New Orleans, Louisiana regarding OSHA requirements for railings. In addition, it confirms your telephone conversation with a member of my staff.

Your basic question requesting an interpretation of 29 CFR 1910.23(e)(3)(v) has been reviewed, especially the (b) part of (v), which reads "A strength to withstand at least the minimum requirement of 200 pounds top rail pressure." The minimum requirement of 200 pounds top rail pressure refers to 1910.23(e)(3)(v), which reads "The anchoring of parts and framing of members for railings of all types shall be of such construction that the completed structure shall be capable of withstanding a load of at least 200 pounds applied in any direction at any point on the top rail."

There are no specific guidelines for relating the 200 pounds strength requirement to a stress design criteria. The yield strength of a material is a good guide, providing the railing protects the employee in compliance with the above 1910.23(e)(3)(iv) standard.

If I may be of any further assistance, please feel free to contact me.

Sincerely,

John K. Barbo, Chief
Division of Occupational Safety Programming

Figure H-4. OSHA specification cited by Hollaender Certificate of Compliance. Certifies that rail system made with Speed Rail connectors can withstand at minimum a 200 pound point force.
Speed-Rail® Maintenance Manual

All aluminum components of this handrail system have an anodized finish that is exceptionally resistant to corrosion, discoloration, and wear. Periodic maintenance is necessary only to prevent the long-term accumulation of soil, which, under certain conditions, can accelerate the weathering of the finish. The geographic area and environmental conditions will determine the frequency and method of cleaning. Several progressively stronger cleaning procedures may be used depending on the severity and tenacity of the soil. Trial and error testing, beginning with the simplest procedure, will determine which will be the most effective.

All fasteners used in the Interna-Rail handrail system are 304 stainless steel alloy, and are designed to be permanently locked. They should not require periodic maintenance under normal conditions. However, there may be exceptions under conditions of excessive vibration, or where an impact load has occurred that may require a retightening of setscrews or anchor bolts. A periodic inspection of the handrail system by physically moving the top rail back and forth will reveal any need to retighten the fasteners. If any looseness to the system has occurred the following torque settings are recommended:

- 3/8" dia. setscrew at #155 tee (rail to post): 26 ft-lbs
- 3/8" dia. setscrews at post to base flange: 17 ft-lbs
- 3/8" dia. anchor bolts at base flange: 25-50 ft-lbs (2"). dia. anchor bolts at base flange: 40-80 ft-lbs

Cleaning Procedures

1. For light or loose soil flush surface with water using moderate pressure.

2. For moderate soil wash with a mild soap or detergent, that can be applied with bare hands, on a soft cloth or sponge then rinse with clean water.

3. To remove oil, grease, wax, or polishes use a solvent such as lacquer thinner applied with a soft cloth. Surface can then air dry.

4. Heavy soil can be removed with an abrasive-cleaning pad soaked with clean water or detergent. Scrub in the direction of the metal grain (along the length of pipe). Rinse thoroughly with clean water to remove residue from pad or cleaner. Care must be taken to ensure that metal seams and crevices that may trap dirt, cleaner, or other material are rinsed clean.

Cleaning Precautions

1. Never use chlorine bleach, trisodium phosphate, highly alkaline, or highly acid cleaners.

2. Etching cleaners should never be used on anodized aluminum.

3. Avoid excessive rubbing with abrasive cleaners, scouring pads, brushes, or steel wool. Also, steel wool must be thoroughly rinsed off surface to remove steel particles that may rust.

4. Do not use power tools with wire brushes, abrasive pads, or polishes that may scratch or abrade the anodized surface.

Figure H-5. Maintenance procedures and torque specifications for connectors.
Figure H-6. Specifications for the vinyl-coated polyester fabric that will cover the backdrop.
Appendix I: Assembly Instructions

Safety Procedures:

It is your duty to follow these Safety Procedures to avoid getting injured in any way while assembling each and every component of the “Mobile Opera Backdrop”.

Assembly: To be perform by 2 or more people

Open space:

a. Begin by finding a large space to work.
b. Clear the space from any Hazardous objects (Large rocks, cords, instruments, etc.).
c. Make sure the space is on a flat ground to avoid tilting.

Lifting:

a. For lifting objects off the ground:
   i. Stand close to the object, with your feet shoulder-width apart and your toes naturally pointed outward.
   ii. Squat down next to the object by bending at your knees and hips, maintain your back’s natural curves.
   iii. Pull the load close to you and grasp it firmly.
   iv. As you rise with the load, lift with your legs. Use your strong leg muscles, Not your back muscles, to power the lift.
   v. While lifting, keep your back straight.
   vi. Raising your chin while lifting will help your back maintain its natural curves.

b. For Lifting above your head:
   i. If using a helping tool (foldable chair, stool, or ladder) to lift object to its corresponding height have a second person hold and secure the helping tool.

   Ask for help when you need to lift a heavy load. Be willing to help others with heavy loads and be willing to ask others to help you. When you lift, always use this technique. If you do not, you could be setting yourself up for a painful injury. And once you injure your back, you are more likely to injure it again.

Dress Code:

a. Wear comfortable clothes, long pants are required, No baggy shirts.
b. Closed-toed shoes are required to avoid any foot injuries.
c. No hanging accessories (key chains, earphones, etc.) to avoid any tangling with any object

   The dress code is designed first and foremost for safety reasons. The type of clothing that is required of workers and volunteers is intended to protect these individuals from any danger.
Component Codes

Each component is stamped with an alphanumeric code to indicate the component’s proper installation location and orientation.

Table 1. Each component type has a corresponding code letter.

<table>
<thead>
<tr>
<th>Code Letter</th>
<th>Component Type</th>
<th># of Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Arch pipe</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>Diagonal pipe</td>
<td>4</td>
</tr>
<tr>
<td>M</td>
<td>Middle pipe</td>
<td>4</td>
</tr>
<tr>
<td>P</td>
<td>Push Arm</td>
<td>4</td>
</tr>
<tr>
<td>R</td>
<td>Rear pipe</td>
<td>4</td>
</tr>
<tr>
<td>S</td>
<td>Side pipe</td>
<td>4</td>
</tr>
<tr>
<td>V</td>
<td>Vertical pipe</td>
<td>6</td>
</tr>
<tr>
<td>A</td>
<td>Adjustable connector</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>Corner connector</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>Elbow connector</td>
<td>4</td>
</tr>
<tr>
<td>T</td>
<td>Tee connector</td>
<td>14</td>
</tr>
<tr>
<td>S</td>
<td>Straight connector</td>
<td>4</td>
</tr>
</tbody>
</table>

Pre-Assembly Setup
To expedite the assembly process, lay out and organize the components into the groups listed in Table 1. Count the components to check that none are missing.

Note:

1. Each pipe will be marked to the depth to which it must be inserted into its corresponding connector. This applies to all pipes in the assembly.
2. All fabrics will be attached such that the matte finish of the material is facing towards the audience.
Section 1: Base Assembly and Fabric attachment

1. Insert pipes R and S1 into connector C1. Point the bare end of pipe S1 towards where the audience will be located.
2. Install connector E onto the end of pipe S1.
3. Install connector T1 onto the end of pipe R.
4. Insert V1 pipes (x2) into connectors C1 and T1.
5. Insert pipe V2 into connector E.
6. Slide connector T2 onto pipe V1 until level with top of stage.
7. Slide A1 connectors (x2) onto V1 pipes (x2).
8. Slide connector A2 onto pipe V2.
9. Insert pipe D1 into A1 connectors (x2).
10. Insert pipe D2 into connector A2 (x2).
11. Install connector C2 onto the end of pipe V1.
12. Install connector E onto the end of pipe V1.
13. Insert pipe R into connectors C2 and E.
15. Attach endplates at end of pipes S2 and V2.
16. Install pipe A (x2) at endplate.
17. Install connector S (x2) onto the end of pipe A (x2).
18. Attach the rectangular fabric above using the ball bungees.
19. Repeat steps 1 through 18 for the Stage-Left Base assembly

Section 2: Connection of Base Assemblies (Rear View)

1. Insert pipe M1 into connector T (x2).
2. Insert pipe M1 into connector T (x2).

Section 3: Overhang Assembly
1. Start with the right side of the overhang and place A1 in its appropriate location as shown, where the long tangent side of the curved pipe attaches to the endplate.
2. Pass the bolt and washers through the endplate hole.
3. Tighten the bolt in place by using a nut.
4. Repeat steps 1 through 3 for A2.
5. Repeat steps 1 through 4 for the left side of the overhang.
6. Insert connector S into the short tangent side of A1 curved pipe (Right side).
7. Insert connector S into the short tangent side of A1 curved pipe (Left Side).
8. Insert M2 into connectors S.
9. Tighten the set screws on both straight connectors S.
10. Repeat steps 6 through 9 for the A2 curved pipe.

Section 4: Upper Arch Deployment and Fabric Attachment
1. With the upper arch connected to the endplate, attach the top edge of the above fabric to the top arch tubes using ball bungees.

2. Simultaneously, insert the push arm P into the upper T connectors.

3. Using an Allen key, tighten the setscrews connecting P to the upper T’s, but do not tighten the setscrews connecting T to the curved pipes.

4. Each of the two assemblers must simultaneously push P upwards and slot the lower end of P into the lower set of connectors, T.

5. Using a ladder, complete the attachment of the fabric so that it is located between the sets of arches.

Section 5: Lower Arch Deployment and Fabric Attachments
1. Attach the top edges of the irregular-shaped fabric above to the lower arch tubes using ball bungees.
2. Simultaneously, insert the push arms, P, into the free set of T connectors on the upper arch tubes.
3. Using an Allen key, tighten the setscrews connecting P to the upper T’s, but do not tighten the setscrews connecting T to the curved pipes.
4. Each of the two assemblers must simultaneously push P upwards and slot the lower end of P into the lower set of connectors, T.
5. Allowing a 2.5 inch space between the lower set of T and E connectors, tighten all the setscrews on the lower set of T connectors.
6. Using a ladder, complete the attachment of the fabric so that it is located between the base and the lower arch tubes.
7. In addition, attach the rectangular fabric to fit between the two rear P tubes and against the pipe connecting the arches together.
## Appendix J: Replacement Parts

<table>
<thead>
<tr>
<th>Component</th>
<th>Image</th>
<th>Vendor</th>
<th>P/N</th>
</tr>
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<tbody>
<tr>
<td>Aluminum Tubing</td>
<td>![Image]</td>
<td>Buyrailings.com</td>
<td>51-A112ID</td>
</tr>
<tr>
<td>Elbow Connector</td>
<td>![Image]</td>
<td>Buyrailings.com</td>
<td>8020</td>
</tr>
<tr>
<td>Tee Connector</td>
<td>![Image]</td>
<td>Buyrailings.com</td>
<td>8070</td>
</tr>
<tr>
<td>Corner Connector</td>
<td>![Image]</td>
<td>Buyrailings.com</td>
<td>8120</td>
</tr>
<tr>
<td>Straight Connector</td>
<td>![Image]</td>
<td>Buyrailings.com</td>
<td>8630</td>
</tr>
<tr>
<td>Component</td>
<td>Image</td>
<td>Vendor</td>
<td>P/N</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------</td>
<td>--------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Adjustable Connector</td>
<td><img src="image1.png" alt="Image" /></td>
<td>Buyrailings.com</td>
<td>8230</td>
</tr>
<tr>
<td>Vinyl-Coated Polyester (30'x30')</td>
<td><img src="image2.png" alt="Image" /></td>
<td>Mytarp.com</td>
<td>VCT183030BLK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Request no hemming or grommets)</td>
</tr>
<tr>
<td>Ball Bungees</td>
<td><img src="image3.png" alt="Image" /></td>
<td>Mytarp.com</td>
<td>BB06-50</td>
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</table>
## Appendix K: DVP

**TEST PLAN**

<table>
<thead>
<tr>
<th>Item No</th>
<th>Specification #</th>
<th>Test Description</th>
<th>Acceptance Criteria</th>
<th>Test Responsibility</th>
<th>Test Stage</th>
<th>SAMPLES TESTED</th>
<th>TIMING</th>
<th>TEST RESULTS</th>
<th>TEST REPORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106-T</td>
<td>Buckling calculations on the front vertical tubes to justify wall thickness against buckling</td>
<td>No visual deflection or buckling failure</td>
<td>Kevin Valencia</td>
<td>SP</td>
<td>1</td>
<td>C</td>
<td>1/8/2018</td>
<td>1/25/2018</td>
</tr>
<tr>
<td>2</td>
<td>301-P</td>
<td>Hand calculations to size the thickness of the endplates</td>
<td>SF = 5</td>
<td>Kevin Valencia</td>
<td>SP</td>
<td>1</td>
<td>C</td>
<td>1/8/2018</td>
<td>1/25/2018</td>
</tr>
<tr>
<td>3</td>
<td>301-P</td>
<td>Structural prototype to analyze structural integrity of the endplate and any manufacturing difficulties</td>
<td>No pinning pipe collision and functional prototype</td>
<td>Robbie Behlman</td>
<td>SP</td>
<td>1</td>
<td>Sub</td>
<td>1/8/2018</td>
<td>1/30/2019</td>
</tr>
<tr>
<td>4</td>
<td>201-T</td>
<td>FEA bending stress analysis by applying vertical load along the arch center tube to predict failure</td>
<td>Less than 0.5&quot;</td>
<td>Kevin Valencia</td>
<td>SP</td>
<td>1</td>
<td>C</td>
<td>1/8/2018</td>
<td>1/29/2018</td>
</tr>
<tr>
<td>5</td>
<td>201-T</td>
<td>FEA simulation on the entire structure to measure the deflection effects caused by the weight of loads and the tarp</td>
<td>Less than 0.5&quot;</td>
<td>Robbie Behlman</td>
<td>SP</td>
<td>1</td>
<td>Sys</td>
<td>1/8/2018</td>
<td>2/1/2018</td>
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<tr>
<td>6</td>
<td>109-C</td>
<td>A bending stress test on setcrews by fixing a T-connector in a vise and applying a moment via the attached pipe. This will determine the moment required before the setcrews begin to slip</td>
<td>10&quot; setcrew rotation</td>
<td>Kevin Valencia</td>
<td>FP</td>
<td>1</td>
<td>Sub</td>
<td>5/2/2019</td>
<td>5/24/2019</td>
</tr>
<tr>
<td>7</td>
<td>109-C</td>
<td>A tension test on setcrews by fixing a T-connector in a vise and applying tension via the attached pipe. This will determine the tension required on the pipes before the setcrews begin to slip</td>
<td>10&quot; setcrew rotation</td>
<td>Robbie Behlman</td>
<td>FP</td>
<td>1</td>
<td>Sub</td>
<td>5/2/2019</td>
<td>5/24/2019</td>
</tr>
<tr>
<td>8</td>
<td>207-F</td>
<td>Sound test to measure any increase in sound level.</td>
<td>Sound intensity 50% of plywood reference</td>
<td>Robbie Behlman</td>
<td>FP</td>
<td>1</td>
<td>Sub</td>
<td>5/2/2019</td>
<td>5/24/2019</td>
</tr>
<tr>
<td>9</td>
<td>207-F</td>
<td>Tear test on sample fabrics to determine the durability and appearance of the fabric</td>
<td>No tearing, excessive wrinkling</td>
<td>Kevin Valencia</td>
<td>FP</td>
<td>1</td>
<td>Sub</td>
<td>5/2/2019</td>
<td>5/24/2019</td>
</tr>
</tbody>
</table>

**Figure I-1.** DVP table showing the tests already performed with the results and planned tests
Appendix L: Test Procedures

Test 1: Pipe Deflection

**Location:** This experiment will be conducted in Cal Poly’s Bonderson building. The test will be set-up in the space in front of the Mustang 60 machine shop entrance. To replicate this test, a space with a 10 ft. radius, sturdy table, two C-clamps, two V-blocks, four ft long 1-1/2” IPS 6061 Aluminum schedule 40 pipe, bucket of water, chain, two bolts, six ft long string, tape, and calipers are required.

**Safety Procedures:** The greatest concern with this test experiment is securely fixing one end of the pipe. As a result, at least two C-clamps should be used to secure the pipe and force should be applied on the pipe manually to identify any possible slip of the pipe prior to loading with higher weight. In addition, close-toed shoes are advised as the falling of heavy objects could occur.

**Data Collection/Documentation:** From this experiment, the weight which the horizontal pipe connecting the two curved pipes can endure without permanently deflecting more than a quarter inch will be determined. Once the weight to deflect the beam a quarter inch is determined, the loading capacity will be set using a safety factor of two.

**Set-Up:** On the edge of a sturdy table, slide the pipe in between two V-blocks, with the vertices aligned vertically. Secure the pipe by clamping the V-blocks to the table using at least two C-clamps. To measure the deflection of the pipe, tape a string to the top of the fixed end of the pipe and tape the other end of the string horizontally to a nearby wall. The pipe can be loaded by wrapping a length of chain around pipe near the free end. By passing a bolt through both the chain and the drilled holes, the chain will be fixed and overhanging so that weights could be attached to it. By passing the two overhanging lengths of chain around a bucket’s handle, the chains could be constrained by a bolt with a nut on the other end passed through. With the experiment set-up, the bucket could be loaded with water. In intervals of five pounds, the weight and the corresponding deflection could be recorded. The deflection is recorded using calipers, measuring from the top of the deflected beam end to the horizontal string. The experiment set-up could be disassembled by raising the bucket of water and removing the bolt attaching to the hanging chain. While holding the pipe firmly, the C-clamps could be loosened.
Test 2: Connector Setscrew Slip Due to Bending

Location: This experiment will be conducted in Cal Poly’s Bonderson building. The test will be set-up in the space in front of the Mustang 60 machine shop entrance. To replicate this test, a space with a 5 ft. radius, sturdy table, two C-clamps, two V-blocks, four ft long 1-1/2” IPS 6061 aluminum schedule 40 pipe, 1-1/2” IPS aluminum tee connector, bucket of water, chain, two bolts, and a marker are required.

Safety Procedures: The greatest concern with this test experiment is securely fixing one end of the pipe. As a result, at least two C-clamps should be used to secure the pipe and force should be applied on the pipe manually to identify any possible slip of the pipe prior to loading with higher weight. In addition, close-toed shoes are advised as the falling of heavy objects could occur.

Data Collection/Documentation: From this experiment, the force which will result in slipping of the connector setscrews due to bending will be determined. The pipe will be loaded to failure, resulting in any single setscrew slipping. Once the weight to untighten the setscrew is determined, the loading capacity will be set using a safety factor of two. Wind load calculations at 30 mph will determine if the force required to untighten the setscrews due to bending is a concern.

Set-Up: On the edge of a sturdy table, slide the pipe in between two V-blocks, with the vertices aligned vertically. Secure the pipe by clamping the V-blocks to the table using at least two C-clamps. The pipe can be loaded by wrapping a length of chain around pipe near the free end. By passing a bolt through both the chain and the drilled holes, the chain will be fixed and overhanging so that weights could be attached to it. By passing the two overhanging lengths of chain around a bucket’s handle, the chains could be constrained by a bolt with a nut on the other end passed through. With the experiment set-up, the bucket could be loaded with water. In intervals of five pounds, the weight and the corresponding effect could be recorded. The experiment set-up could be disassembled by raising the bucket of water and removing the bolt attaching to the hanging chain. While holding the pipe firmly, the C-clamps could be loosened.
Test 3: Connector Setscrew Slip Due to Torsion

**Location:** This experiment will be conducted in Cal Poly’s Bonderson building. The test will be set-up in the space in front of the Mustang 60 machine shop entrance. To replicate this test, a space with a 5 ft. radius, sturdy table, two C-clamps, two V-blocks, four ft long 1-1/2” IPS 6061 aluminum schedule 40 pipe, 1-1/2” IPS aluminum tee connector, bucket of water, chain, two bolts, and a marker are required.

**Safety Procedures:** The greatest concern with this test experiment is securely fixing one end of the pipe. As a result, at least two C-clamps should be used to secure the pipe and force should be applied on the pipe manually to identify any possible slip of the pipe prior to loading with higher weight. In addition, close-toed shoes are advised as the falling of heavy objects could occur.

**Data Collection/Documentation:** From this experiment, the force which will result in slipping of the connector setscrews due to torsion will be determined. The pipe will be loaded to failure, resulting in any single setscrew slipping. Once the weight to untighten the setscrew is determined, the loading capacity will be set using a safety factor of two. Wind load calculations at 30 mph will determine if the force required to untighten the setscrews due to torsion is a concern.

**Set-Up:** On the edge of a sturdy table, slide the pipe in between two V-blocks, with the vertices aligned vertically. Secure the pipe by clamping the V-blocks to the table using at least two C-clamps. The pipe can be loaded by wrapping a length of chain around pipe near the free end. By passing a bolt through both the chain and the drilled holes, the chain will be fixed and overhanging so that weights could be attached to it. By passing the two overhanging lengths of chain around a bucket’s handle, the chains could be constrained by a bolt with a nut on the other end passed through. With the experiment set-up, the bucket could be loaded with water. In intervals of five pounds, the weight and the corresponding effect could be recorded. The experiment set-up could be disassembled by raising the bucket of water and removing the bolt attaching to the hanging chain. While holding the pipe firmly, the C-clamps could be loosened.
Test 4: Connector Setscrew Slip Due to Extended Time Usage

**Location:** This experiment will be conducted in Cal Poly’s Bonderson building. The test will be set-up in the outdoor space adjacent to the Mustang 60 machine shop check-in window. To replicate this test, a 10’x20’x15’ space will be required. The entire inventory included in the bill of materials will be required, which includes the straight piping, curved piping, pipe connectors, endplates, nuts, bolts, torque wrench, socket set, and compass.

**Safety Procedures:** The assembly manual should be adhered to at all moments when assembling the structure. At least two individuals should be involved in the assembly and coordination is required. In addition, since the test duration is 24 hours, the structure’s immediate surrounding area should be closed off and labeled as a potential hazard zone should the structure collapse.

**Data Collection/Documentation:** From this experiment, the stationary ability of the structure to remain assembled without any significant setscrew slippage occurring will be tested. Should the connectors pass the test, the angular displacement of the setscrew will be measured using a protractor.

**Set-Up:** Following the directions in the assembly manual, the frame will be assembled by two individuals. The frame will then be left in the assigned storage space untampered with for 24 hours. Using warning tape attached to a series of parking cones surrounding the frame, the immediate area will be closed off. Warning signs will be posted, advising the public of the possible collapse hazard. At the conclusion of the test, the assembly manual will be referred to again in order to properly disassemble the frame.
Test 5: Fabric Sound Reflectivity

Location: Perform this test in a sound controlled environment where external noise sources will not disrupt the recording. This test will require a sample fabric material, microphone, an amplifier, synthesizer, looping pedal, computer, and recording software.

Safety Procedures: No special safety equipment required. Be mindful of tripping hazards caused by wiring to amplifier, synthesizer, looping pedal, microphone, computer and recording hardware. Avoid loud test signals to reduce risk of hearing damage.

Data Collection/Documentation: This test will capture the relative sound reflectivity of the backdrop fabric compared to plywood, the industry standard. The sound level in decibels will be recorded, from which sound intensity can be calculated and compared.

Set-Up: Fixate a 2’x2’ square of material in a vertical orientation. Place a microphone 3” from and perpendicular to the material with the microphone pointing towards the material. Place an amplifier 15” from and perpendicular to the material, with the speaker in the amplifier pointing towards the material. Connect a synthesizer to a looper pedal that connects to the amplifier. Begin a loop on the looper pedal, then record a C-chord on the synthesizer. End the loop on the looper pedal. Run the loop on repeat, then begin the recording software. Run a peak meter to capture the maximum decibels of each sound loop. Record twenty loops, then replace the fabric with plywood to compare the sound reflection properties.
Test 6: Fabric Tearing/Tensioning

Location: We will be testing outside the Cal Poly Bonderson building, but this test could be performed at any location where there is an elevated fixed horizontal pipe and heavy objects are allowed to strike the ground. This test requires two 2’x2’ grommeted fabric samples (vinyl coated polyester and polyester canvas), string, five pound weights, knife, and a fixed horizontal pipe from where to hang the fabric.

Safety Procedures: During this test, close-toed shoes are required and caution must be taken to avoid foot injuries.

Data Collection/Documentation: This test will determine the tension that the fabric could endure without tearing. In addition, the test will test the difficulty and effect of puncturing each tensioned material.

Set-Up: Each sample fabric has at least six inches of string tied to each of the grommeted holes. The other end of the string from one side of the fabric is tied to a fixed horizontal tube. On the opposite side of the fabric, weights are tied to the free end of the strings. If the fabric withstands, an increase in weight is made and observations are recorded. In addition, the fabric will be tensioned between two fixed pipes and the fabric will be punctured to determine the ease and effect of puncturing. If the material tears when punctured, the material consideration must be discarded and preference should be given to the next contender that provides an acceptable sound reflectivity and material strength balance.
Appendix M: Uncertainty Analysis (Deflection due to Torsion Test)

\[
\text{Deflection of pipe per unit of torque} = \frac{\text{Deflection}}{\text{Torque}}
\]

\[
\frac{\text{Deflection}}{\text{Torque}} = \frac{\Delta}{\Gamma} = \frac{d}{\Gamma T}
\]

\[
U_d = \pm 0.0005 \text{ in}
\]

\[
U_T = \pm 0.05 \text{ lb}
\]

\[
U_f = \pm \frac{1}{32} \text{ in} = \pm 0.03125 \text{ in}
\]

\[
U_{\Delta f \alpha} = \frac{\partial \Delta}{\partial d} U_d = \frac{\partial \Delta}{\partial (d - U_d)} - \frac{\partial \Delta}{\partial (d + U_d)}
\]

\[
U_{\Delta f \epsilon} = \frac{\partial \Delta}{\partial \epsilon} U_f = \frac{\partial \Delta}{\partial (\epsilon - U_f)} - \frac{\partial \Delta}{\partial (\epsilon + U_f)}
\]

\[
U_{\Delta f \Gamma} = \frac{\partial \Delta}{\partial \Gamma} U_T = \frac{\partial \Delta}{\partial (\Gamma + U_T)} - \frac{\partial \Delta}{\partial (\Gamma - U_T)}
\]

\[
U_{\Delta f \gamma} = \pm \sqrt{\left( U_{\Delta f \alpha}^2 + U_{\Delta f \epsilon}^2 + U_{\Delta f \Gamma}^2 \right)}
\]
First measurement, \( d = 0.38 \text{ in.}, F = 16.2 \text{ lb}, r = 66 \text{ in.} \)

\[
U_{\text{meq}} = \frac{D \cdot (0.38 \text{ in.} - 0.035 \text{ in.}) - D \cdot (0.78 \text{ in.} - 0.035 \text{ in.})}{2}
\]

\[
= \frac{D \cdot (0.38 \text{ in.} - 0.035 \text{ in.}) - D \cdot (0.78 \text{ in.} - 0.035 \text{ in.})}{2}
\]

\[
= 4.78 \times 10^{-4} \text{ in.}
\]

\[
U_{\text{meq}} = \frac{D \cdot (16.2 \text{ lb} - 0.05 \text{ lb}) - D \cdot (16.2 \text{ lb} - 0.05 \text{ lb})}{2}
\]

\[
= \frac{D \cdot (16.2 \text{ lb} - 0.05 \text{ lb}) - D \cdot (16.2 \text{ lb} - 0.05 \text{ lb})}{2}
\]

\[
= 7.29 \times 10^{-6} \text{ in.}
\]

\[
U_{\text{meq}} = \frac{D \cdot (66 \text{ in.} + 0.025 \text{ in.}) - D \cdot (66 \text{ in.} - 0.025 \text{ in.})}{2}
\]

\[
= \frac{D \cdot (66 \text{ in.} + 0.025 \text{ in.}) - D \cdot (66 \text{ in.} - 0.025 \text{ in.})}{2}
\]

\[
= 3.45 \times 10^{-6} \text{ in.}
\]

M-2
\[
U_{D,t} = \pm \sqrt{ \left( U_{D,t,1} \right)^2 + \left( U_{D,t,2} \right)^2 + \left( U_{D,t,3} \right)^2 }
\]

\[
= \sqrt{ \left( 4.25 x 10^{-5} \text{ in} \right)^2 + \left( 2.25 x 10^{-6} \text{ in} \right)^2 + \left( 2.45 x 10^{-6} \text{ in} \right)^2 }
\]

\[
= \sqrt{5.912 \times 10^{-2} \text{ in}}
\]

\[
U_{D,t} = 2.32 \times 10^{-6} \text{ in/in/16} = 2.79 \times 10^{-5} \text{ in/ft/in}
\]

Nominal deflection \( D/t \) = \( \frac{0.78 \text{ in}}{(16.2/16)(5.5/1)} \) = \( 0.75 \times 10^{-3} \text{ in/ft/in} \)

When a torque is placed on a pipe with a supported connector on one end and no support on the other, the pipe will deflect

\( 8.75 \times 10^{-3} \text{ in} \pm 2.79 \times 10^{-5} \text{ in} \)

per foot-pound of torque.
Appendix N: Gantt Chart

<table>
<thead>
<tr>
<th>Date</th>
<th>People Assigned</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/25</td>
<td>Jue Villabos</td>
<td>100</td>
</tr>
<tr>
<td>1/26</td>
<td>Jue Villabos</td>
<td>100</td>
</tr>
<tr>
<td>1/27</td>
<td>Jue Villabos</td>
<td>100</td>
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<td>1/28</td>
<td>Jue Villabos</td>
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<td>Jue Villabos</td>
<td>100</td>
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<tr>
<td>1/30</td>
<td>Jue Villabos</td>
<td>100</td>
</tr>
<tr>
<td>1/31</td>
<td>Jue Villabos</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure K-1. Our Gantt Chart provides us with a quick way to assign tasks to individual team members and to maintain steady progress throughout the year.
Appendix O: Operators Manual 2

Quick Deployment Guide

The following guide is designed to provide a set of easy-to-follow instructions for setting up the backdrop prior to a performance. These instructions assume the backdrop has been removed from the transport vehicle with all fabric sections attached, minus the two rectangular fabric sections that connect between the two halves. Deployment requires a minimum of two people.

Equipment needed:

- Allen Key: 3/16 ”
- Center Pipe A: 53”
- Center Pipe B: 50”
- Center Pipe C: 54” (Quantity: 2)
- Push Arm Pipes (Quantity: 4)
- Ball Bungees
- Ladder (Optional)

Step 1: Initial Setup

- Remove the two halves of the backdrop from the transport vehicle.
- Place the two halves of the backdrop at either side of the stage.
  - Leave a 6” gap between each side of the stage and the side of each backdrop half.
  - Place the rear of each backdrop half flush with the rear of the stage.
Figure 1. The two halves of the backdrop placed in position (stage not shown).

- **NOTE:** To conserve storage space, the halves should be nested together (as shown in Figures 2 and 3) inside the transport vehicle.

Figure 2. Front view of the two halves of the frame nested together.

Figure 3. Top view of the two halves of the frame nested together.
**Step 2: Install Center Pipe A**

- Insert Center Pipe A into the tee-connectors at the bottom corner of each backdrop half as shown in Figure 4.
- Using the 3/16” Allen key, tighten the connector set screw on one side.
- **DO NOT** tighten the set screw on the other side until the next step is completed.

![Center Pipe A](image)

**Figure 4. Center Pipe A attached to both backdrop halves.**

**Step 3: Install Center Pipe B**

- Insert Center Pipe B into the tee-connectors as shown in Figure 5.
  - In order to fit Center Pipe B, the vertical pipe of one of the backdrop halves needs to be pushed outward.
  - Once the pipe is in place, tighten the set screws on both sides.
- Go back to Center Pipe A and tighten the other set screw. Before fully tightening the set screws, make sure that the structure is properly square with the stage and not tilting in any direction.
Figure 5. Center Pipes A and B attached to both frame halves.

**Step 4: Install Center Pipes C**

- Install Center Pipes C to connect the curved pipes of each backdrop half as shown in Figure 6.
  - Insert each end of each Center Pipe C into one of the
- Moving on to connecting the curved pipes with each other. Begin by inserting one of the horizontal pipes A into the straight connectors attached to each end of the curved pipes and tighten the set screws use Figure 6 as reference. Make sure the horizontal pipe is parallel to the ground.
Figure 6. All center pipes installed connecting the two halves together.

Figure 7. The backdrop is now ready for the push arms to be installed.
Step 5: Install Stage 1 Push Arms

- Insert two of the push arms into the tee-connectors located on the top-most pipe on the backside of the backdrop, as seen in Figure 8.
- **IMPORTANT:** Tighten the lower set screws to keep the push arms from vertically slipping out of the connectors.
- Do not tighten the upper set screws that would lock the connectors on the horizontal pipe. The connectors need to rotate when the push arms are raised into position.

![Figure 8. The push arms attached to the frame tee-connectors.](image)

Step 6: Stage 1 Deployment

- Attach the larger rectangular center fabric section to the frame using ball bungees.
  - Start with the top of the fabric which connects to the upper Center Pipe C, shown in Figure 9.
  - Attach the sides of the fabric to the push arms. The lower two grommets on each side do not need to be attached to the push arms at this point.
- Use the push arms to lift the first hoop frame into position. Insert the bottoms of the push arms into the tee-connectors located on the next hoop frame.
- Attach the lower two grommets of the center fabric section to the push arms. Attach the bottom of the center fabric section to the lower Center Pipe C.
Figure 9. Stage 1 Deployment with the center fabric section attached

- **Option:** Raise the first hoop frame without the center fabric section attached, shown in Figure 10. Use a ladder to attach the fabric after the hoop frame is in stage one deployment position.
Figure 10. Stage 1 Deployment without the center fabric section attached.

- **IMPORTANT:** Tighten the set screws in the tee-connectors that hold the push arms in the connectors, as seen in Figure 11. Leave the other set screws loose to allow the connector to rotate.

Figure 11. Ensure to tighten all set screws that hold the push arms in the tee-connectors. Leave the other set screws loose to allow the connectors to rotate around the horizontal pipes.

**Step 7: Install Stage 2 Push Arms**

- Insert the final two push arms into the tee-connectors located on the next hoop frame.
- **IMPORTANT:** Tighten the lower set screws to keep the push arms from vertically slipping out of the connectors.
- Do not tighten the upper set screws that would lock the connectors on the horizontal pipe. The connectors need to rotate when the push arms are raised into position.
Step 7: Stage 2 Deployment

- Attach the smaller rectangular center fabric section to the frame using ball bungees.
  - Start with the top of the fabric which connects to the lower Center Pipe C, shown in Figure 12.
  - Attach the sides of the fabric to the push arms.
- Use the push arms to life the second hoop frame into position. Insert the bottoms of the push arms into the tee-connectors located on the base frame.
- **IMPORTANT:** Tighten the set screws in the tee-connectors that hold the push arms in the connectors, as seen in Figure 11.
Figure 12. The backdrop fully deployed.
NOTE: Some bungees may need to be removed when assembling and disassembling the backdrop to loosen the tension and make it easier to lift and lower the push arms, as shown in Figure 13.

Figure 13. Disconnecting four horizontal bungees and two vertical bungees makes deployment and collapsing of the backdrop easier due to relieved tension.