THE ANALYSIS AND MANUFACTURING OF THE PERSONAL VACUUM ASSISTED CLIMBER II

by

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A thesis submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
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The PVAC or **Personal Vacuum Assisted Climber** (shown in Fig 1) is a new approach to climbing vertical surfaces. Unlike typical grappling hooks used today, the PVAC uses the principle of a vacuum to rapidly scale walls. This climbing method was successful; it won the 2012 University Design Challenge sponsored by the Air Force Research Lab (AFRL). As a result of winning, further funding was provided to improve upon the original version of the PVAC. The objectives of this project are:
• Weight optimization to reduce climbing fatigue

• Ergonomic advancements to make ascending walls intuitive and easy

• Manufacturing improvements to save on time and money

• Passive noise reduction

To address these issues, several analysis techniques, as well as testing have been conducted. Weight reduction was reassessed using the following techniques:

• Finite Element Analysis (FEA)

• Materials trade study

To determine the ergonomic enhancements, literature studies were conducted to make the system comfortable to operate. Several test climbs were made to examine the functionality of the new system and to fix any bugs within the system. Lastly, manufacturing techniques have been addressed in each subsystem to make the PVAC easier and cheaper to manufacture and assemble. This was done by:

• Reassessed the manufacturing processes used for each component

• Designed for Manufacturing and Assembly (DFMA)

• Determined the cost of multiple \( n \) number of systems

To conclude, tests were conducted to validate that the PVAC system is operating to desired specifications. These tests were conducted in the following areas:

• Sound Reduction

• Battery Voltage Profile

• Temperature Analysis

• Vacuum Motor Performance

• Friction Coefficient Experiments
Overall performance was then compared between the original and new system. Satisfaction of the new design requirements were then determined for the new system. Finally, future applications and improvements were assessed if further versions of the PVAC were to be made.
Public Abstract

The Analysis and Manufacturing of the Personal Vacuum Assisted Climber II

by

Rhet B. Astle, Master of Science
Utah State University, 2014

Major Professor: Dr. Byard Wood
Department: Mechanical and Aerospace Engineering

Fig. 2

The Personal Vacuum Assisted Climber or PVAC for short (as shown in Fig 2) is a new means for climbing walls. Unlike ordinary climbing methods used today, the PVAC scales walls via suction. This suction is produced by three spinning impellers within each vacuum motor, which removes air from a sealed area. A climber pulls down on a vacuum pressure release mechanism to release the vacuum. Foot stirrups are used by the climber to climb to the next higher step. This allows the strength of the climber’s legs to lift his/her body reducing arm fatigue, allowing rapid ascension of any climbable wall.
The overall desirables to accomplish in this project are to make a new system that is:

- Lightweight
- Improved ergonomics
- Easy to manufacture and produce
- Quieter

These items were accomplished by using design tools such as Finite Element Analysis (FEA), Design for Manufacturing and Assembly (DFMA), Failure Modes and Effects Analysis (FMEA), preexisting studies (ergonomics), and testing techniques.

Tests were conducted to ensure that the new PVAC is operating to safe standards. These tests will be looked at in the following areas:

- Sound Reduction
- Battery Voltage Profile
- Temperature Analysis
- Vacuum Motor Performance
- Friction Coefficient Experiments

Lastly, future applications and new improvements were addressed so next generation systems can be made if further development ensues.
To my family... without you, I would be nothing
Acknowledgments

First off, I would like to thank my family for their love and support for this project. I received great input from my family and they helped me design components to what they are now. Initially I had doubts on continuing my education, but my family encouraged me to continue. I would like to thank the original “Ascending Aggies.” I am very thankful to have the great teammates I had. They were very influential to me and I feel that we grew off of each other throughout the design. No matter if we had won or lost the competition, I feel we would have came out winners. I would like to thank the current “2014 Ascending Aggies.” It has been great to work with a new team to put together a completely new design. From this I have gained leadership and management skills that I feel will be useful in the future. I would like to thank Dr. Hansen for being a great design teacher. He was very influential in the “original” design team’s success, and continued to be a great mentor in the current design. Dr. Hansen also never gave up on the project and got the ball rolling when it seemed that all funding was lost. I would like to thank Dr. Byard Wood for the giving great design input. Dr. Wood served as a great major professor, dept. head, and employer. Dr. Hansen and Dr. Wood were not only great professors, but also great friends. I would like to thank God, for the revelation and answered prayers. I would like to thank Jason Jackman and David Drury for hooking me up with the stellar Mi6 rubber. I would also like to thank AcoustiBlok for the material contributions they made as well. And lastly, I would like to thank Zenock Bishop and everybody associated with Senator Orrin Hatch. You truly brought flight to this project. Thanks everyone!

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<td>AFRL</td>
<td>Air Force Research Laboratory</td>
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<tr>
<td>DFMA</td>
<td>Design for Manufacturing and Assembly</td>
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<tr>
<td>EDPM</td>
<td>Ethylene Propylene Diene Monomer (M-Class Rubber)</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<tr>
<td>FMEA</td>
<td>Failure Modes and Effects Analysis</td>
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<tr>
<td>LiPo</td>
<td>Lithium Polymer</td>
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<tr>
<td>PWM</td>
<td>Pulse Width Modulator</td>
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<tr>
<td>PVAC</td>
<td>Personal Vacuum Assisted Climber</td>
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<td>RPC</td>
<td>Risk Priority Code</td>
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Notation

\( A_{suct} \) Effective Suction Area \((in^2)\)

\( F_A \) van der Waals’ adhesion force between two surfaces \((lb.)\)

\( F_C \) Cohesion loss contribution from rubber wear \((lb.)\)

\( F_{\text{climber}} \) Weight of Climber \((lb.)\)

\( F_{Hb} \) Force from Bulk deformation hysteresis in rubber \((lb.)\)

\( F_N \) Normal force applied to paired surfaces \((lb.)\)

\( F_T \) Total frictional resistance between paired surfaces \((lb.)\)

\( n_{safe} \) Safety Factor

\( P_{vac} \) Vacuum Pressure \((psi)\)

\( \sigma_{vM} \) Von Mises Stress \((psi)\)

\( \mu_{\text{stat}} \) Static Coefficient of Friction

\( Y_{yield} \) Material Yield Strength \((psi)\)
Chapter 1
Introduction to the PVAC and Components

Fig. 1.1: PVAC in operation

The Personal Vacuum Assisted Climber (PVAC shown in Fig 1.1) is a new, alternative method for scaling walls. This device arose from a University Design Challenge sponsored by the Air Force Research Laboratories. The design question was: “How do you get four soldiers up a wall without the use of a grappling hook?” The design requirements were as follows:

- Be able to scale a 90 ft (or higher) structure
- Be able to support 300-lbs (vertical)
- Climb a variety of surfaces (glass, adobe, brick, etc.)
- Climb faster than current methods (greater than 12 ft/min)
- Fit inside a 3 cubic foot backpack
The PVAC was designed and built to meet and exceed the stated requirements. The PVAC has many components so for ease of explanation, it will be organized in the following subsystems:

- Pad
- Foot Support
- Vacuum Motor
- Power Delivery
- Safety Devices

A detailed description of each of these subsystems will be in the following subsections.

### 1.1 Pad Subsystem

The pad subsystem shown in Fig 1.2 is comprised of the followings components:

- Aluminum Base
- Fringe (Outer Seal)
- Friction Strips
- Vacuum Hose Quick Connect
- Pressure Release

The aluminum base was the main component of the pad subsystem. The handle, vacuum port, vacuum pressure release, friction strips, instrument panel(with displays), and EVA foam were all fastened to the base. Several locations on the base were drilled or machined to attach these parts. The base along with the fringe (outer seal) and friction strips were used to grip to the surface and hold the climbers weight. The fringe kept the pads attached to the wall by creating an “air tight” seal, whereas the friction strips resisted the shear force at the wall. Air was removed through a quick connector attached to the vacuum hose.
Finally, for climbers to release the pad from the wall, a device called a “vacuum pressure release” was provided. This vacuum pressure release freely rotated up and down exposing a pre drilled hole. When the hole was open, it allowed for the vacuum pressure to be released and new air to circulate in cooling the motors. An extension spring was attached to the vacuum pressure release to spring it back into its original closed position. This allowed the pads to seal and be under vacuum again. This vacuum pressure release provided a fast way to adhere and release from the wall for rapid climbing.

1.2 Foot Support Subsystem

To aid the climber, a foot support system shown in Fig 1.3 was provided to distribute a portion of the climber’s weight to their legs. This allowed the climbers to use their legs, alleviating the need to rely only on upper body strength. This method of climbing has two types of foot support systems:

- Stirrup System
- Ladders

Each of these two options has advantages and disadvantages. For stable and faster climbs, the stirrup system was the optimal choice. This was due to the rigidity of the fiberglass
connection rods that connected the pad subsystem to the stirrups. In addition, prongs with friction-resistant material were attached to the bottom of the stirrups to provide stability for the climber. If overhangs or protruding obstacles were a problem, the ladders were the best choice of foot support for the climber. These ladders were more flexible, which allowed for easier and faster lateral movement.

![Fig. 1.3: (a) Connection of stirrup to fiberglass rods, (b) Ladders with snowboard bindings](image)

1.3 Vacuum Motor Subsystem

The vacuum motor subsystem shown in Figs 1.4 and 1.5 consist of the following:

- Vacuum Motors
- External Backpack

The vacuum motor system consisted of two brushed vacuum motors. Each brushed motor contained:

- (3) Impeller fans
- Tangential exhaust port
- Rotor with (2) carbon brushes
- Metal framed shell
• Hardware to convert AC source to DC (universal vacuum motors)

These motors were chosen because of the high vacuum pressure they produced. The vacuum pressure was achieved by using three-stage impellers, which forced air out of the pad, and created a negative (vacuum) pressure inside the aluminum base. This vacuum pressure allowed for adhesion to the wall and supported the climbers weight. A simple calculation representing vacuum force with respect to climbers weight is shown in Eq 1.1

\[ F_{climber^{safe}} = P_{vac} A_{base} \]  

(1.1)

This equation represents the vacuum force on a flat horizontal surface. When climbing up vertical surfaces, shear forces are present. To overcome shear, a resistive (high coefficient of friction) material was needed to prevent the pads from sliding. This was accomplished by adding a thin strip of high shear rubber, as well as EVA foam sealing material. These materials worked together in tandem to resist the applied shear forces (climbers weight and PVAC weight). Static coefficients of friction were measured through testing to ensure that climbing could be done safely. Further information on the coefficient of friction can be found in Chapter 4.5.

An external frame backpack with motor brackets was used to make carrying this sub-system easy. Extra padding for shoulders and a waist belt was provided to make carrying the pack more comfortable. The frame was designed to distribute the weight of backpack evenly to reduce back strain.

Fig. 1.4: (a) Close up of vacuum motor, (b) Image of backpack frame
1.4 Power Delivery Subsystem

The power delivery subsystem contains the following components:

- Lithium Polymer (LiPO) Batteries
- Vacuum Hoses
- Extension Cord

To provide the power to the vacuum motors, seven lithium polymer batteries were used. An alternative power option was to use an external 120 VAC source with an extension cord that connected to both vacuum motors (shown in Fig 1.6). Vacuum hoses were needed so air could flow from the pads to the vacuum motor exhausts. Using quick connectors, the vacuum hoses (shown in Fig 1.7) snapped into place providing a pathway between pads and vacuum motors.
Fig. 1.6: (a) LiPo battery, (b) Extension cord with power cable connector

Fig. 1.7: Vacuum hose with connector cuffs

1.5 Safety Devices

Safety was a very important aspect of this project. To protect the lives of the climbers, numerous safety features were added Fig to ensure safe climbing (shown in Fig 1.8). These safety features included:

- Vacuum Pressure Gauge
- Voltmeter
- On/Off Switch
- Safety Ring (U-Bolt)
• Daisy Chains

The vacuum pressure gauge provided a visual display of the suction between the wall and pad. Safety marks designated the safe operating range so the climber was fully aware of the vacuum pressure each time the pad was sucked to the wall. A voltmeter indicated how much power was left in the batteries. From the motor specifications, 120 Volts or higher was a safe operating voltage. The LiPo battery provided a constant voltage for around 20 minutes. Beyond that time, a significant voltage drop occurred and the climber had 3-5 minutes before the vacuum motors could no longer provide a safe vacuum pressure. The on/off switch was located next to the voltmeter. It was a basic rocker arm switch, but was recessed inside the instrument panel to prevent accidental shut off. A safety ring (u-bolt) was added, allowing for the climber to attach daisy chains from the harness to the safety ring. Daisy chains are adjustable nylon straps that allow the climber to take a break and "free hang" if the climber gets tired. For military applications, a soldier could stop climbing to fire his/her weapon at any point in the climb, if he/she has the need.

![Fig. 1.8: (a) Instrument panel, (b) Safety ring (U-bolt)]
1.6 Original Testing and Results

The following tests were conducted to make sure the PVAC was working properly prior to the AFRL Design Challenge.

- Battery Testing
- Vacuum Pressure Release Sealing
- Weather Simulation
- Foot Prongs
- Horizontal Climbing

1.6.1 Battery Testing

To validate that the selected LiPo batteries would function to manufactures specifications, the voltage drop as a function of time was measured for the vacuum motors. To take this measurement, the voltmeter on the instrument panel was monitored and recorded every half minute. The test concluded just prior to the batteries reaching their "point of no return". Prior to this point, the batteries can be reliably charged and discharged for several thousand cycles. Beyond this point, the batteries can no longer be (re)charged and should be discarded. Results showed that the batteries had a steady voltage for about 20 minutes, then a significant voltage drop occurred. The results of this test are shown in Fig 1.9. Results showed a linear decrease for the first 20 minutes, and then a significant voltage drop for the next 3-5 minutes.

1.6.2 Vacuum Pressure Release Sealing

When the PVAC was designed, it was thought that the ABS plastic vacuum pressure releases would seal completely. When built and tested, a significant amount of vacuum pressure was lost due to insufficient sealing. To solve this problem, rubberized foam material
with heat shrink tubing encasing the outer edge of the vacuum pressure release was added. Lithium grease was then applied to allow for a smooth sliding action.

1.6.3 Weather Simulation

Since weather at the competition was unknown, tests were needed to simulate possible conditions, such as rain or snow. The hardware of most concern was the vacuum motors. It was thought that if the motors were subjected to harsh conditions, they might short out or seize. Simulations were conducted by attaching the pads to the climbing surface (concrete), then continually spraying the surface with water while opening and closing the vacuum vacuum pressure releases on the pads. This test lasted until the batteries discharged. There were no issues with performance under those conditions.

Another concern was the types of debris that could go through the motors. Water and dust particles went through the motors without issues, but what would happen if the motors were exposed to larger particulates or chunks of rock/cement? A wire mesh was epoxied to the vacuum port to negate this issue. It proved to be effective as the competition surface turned out to be severely weathered concrete silos.
1.6.4 Foot Prongs

During climbing it quickly became apparent that a lot of energy was wasted trying to adjust the climbers center of mass. Besides the suction pads, the toes of the climber’s shoes were the only part gripping the climbing surface. To increase the foot gripping ability, two metal prongs were fastened to each foot stirrup. These prongs were constructed out of (1/8” x 3/4” x 8”) a flat bar and bent at a 90-degree angle an inch from each end. This bent region was then coated with a rubber-based material to add grip. The other end of each flat bar was drilled and riveted to the bottom of the foot stirrups. This simple addition stabilized the climber by gripping the surface, and aided the climber in shifting the center of mass. It resulted in a faster climb.

1.6.5 Horizontal Climbing

As the AFRL Design Challenge neared, the location and pictures of the actual building to be climbed were revealed. The structure to climb was a 90 ft concrete silo with an overhang at the top. Our design team decided to build a mock version of this overhang to see if the PVAC would be able to negotiate the obstacle successfully. A two-foot by four-foot platform was constructed and fastened to the existing test wall. Unfortunately, when we attempted to climb the horizontal surface, the suction pad would not stay attached to the platform. The mechanics were reanalyzed to determine the difference between horizontal and vertical climbing. Even though weight transfer remained straight down, significant differences in pad adhesion were found as the climbing surface changed from parallel (vertical) to perpendicular (horizontal). New safety rings were attached closer to the center of the pads to eliminate the large bending moments that caused peeling and eventually loss of pad suction. This solved the problem. The PVAC was successfully used at the competition to get three members of Air Force Para-Jumpers over the top of the silos, as shown in Fig 1.10.
Fig. 1.10: Para-Jumper climbing over the top of silo
Chapter 2

Mark II PVAC Improvements and Requirements

After several months and a few design iterations, a new PVAC has been built. This new version is more lightweight, easier to manufacture, more cost effective, quieter, and more ergonomically sound. This model is subjected to new design requirements listed below:

2.1 Pad Requirements

- Weight of each pad shall not exceed 4-lbs (Suggested by Cacha [1, pg. 83])
- Each pad must support 300-lbs (soldier and backpack)
- Handle diameter must be at least 1.25-1.5 inches to obtain maximum grip (Suggested by Cacha [1, pg. 83])
- Grip length must be at minimum 4.5 inches to enhance grip (Suggested by Cacha [1, pg. 83])

2.2 Foot Support Requirements

- Foot supporting components must hold at least 300-lbs.
- Connection material must hold at least 300-lbs.
- Connecting/Safety devices must hold at least 300-lbs.

2.3 Backpack Requirements

- Must have a noise reduction of greater than 20 dB
- Must have a monitor of battery life, vacuum pressure, and motor temperature
• Must operate both by battery and 120 VAC external power source

• Must have an operation time of greater than 20 minutes (batteries)

• The noise reduction and monitoring equipment must add a maximum of 10-lbs. of new weight (Desired goal is to reduce weight)
After several months of redesign, improvements were made in the following areas:

- Weight Minimization
- Enhanced Ergonomics
- Manufacturing Ease
- Failure Modes and Effects Analysis (FMEA)

Each of these improvements will be addressed in more detail in the next sections. Further sections including drawing package, manual for assembly, operating manual, and maintenance instructions can be found in Appendices C, D, E, F.

3.1 Weight Minimization

In order to make climbing time more sustainable, a lighter weight PVAC system was required. Several steps were taken to ensure the new design reduced weight, but still was structurally stable. First, geometric modifications were addressed by improving ergonomics and ease of manufacturing. Next, materials were reanalyzed to see if better choices (lighter, less expensive) could replace the original material. Lastly, finite element analysis was used to ensure any newly selected material would meet the required loads.

3.1.1 Material Trade Study

To ensure that the best materials were selected for the job, several trade studies were conducted on the following components:

- Pad Base
• Fringe Sealing Material

• Foot Connection

• Vacuum Motors

• Backpack Shell

• Noise Reduction Material

**Pad Base Selection**

Some or the desire attributes for the base were:

- Lightweight

- Easy to machine

- Low cost

- Relatively large yield stress

- High cycles to failure

**Fig 3.1** is the material trade study for the base. This was the original trade study, updated to reflect changes to the new system. The key difference is the grade of aluminum used. The new version uses strain hardened (cold worked) 5052-32 aluminum because it is the only high strength aluminum that could be metal spun. Aluminum 6061-T6 could not be used for the metal spinning process due to the hardness of the material.
Fringe Sealing Material

In order to pick the best sealing material, several factors were considered:

- Can this material resist shear under vacuum load?
- Can this material recover quickly after compression?
- Is this material a closed-cell foam for efficient sealing?
- Is the tensile strength above five psi to prevent ripping?

Attached is the material selection study for the fringe (see Fig 3.2). EVA foam is the material of choice because of its ability to meet the requirements stated above. It has been extremely durable resisting the wear and tear from testing and hundreds of climbs. Other materials such as EDPM rubber, neoprene, and polyethylene have been tested. They either have ripped and tore under test climbs or were unable to create an adequate seal.
The desired characteristics of the foot connecting material were:

- Lightweight
- Excellent in lateral deflection
- Moderate tensile strength

Polyester webbing proved to be the optimal material. This webbing has excellent tensile strength, abrasive resistance, is extremely lightweight, and can be easily adjusted for various user heights (shown in Fig 3.3). Fig 3.4 shows the trade study used.
Vacuum Motors

The vacuum motors were reassessed to see if there was a way to reduce weight in the backpack system. The original motor specifications required seven batteries wired in series to power each 120-volt AC/DC (universal) motor. These batteries were a major contribution to the system weight, as each battery weighed a little over one lb. each. If the effective
suction area of the pads could be increased, more options for vacuum motors would be available. New motor selection studies (Fig 3.5) showed that 36 VDC motors could be used to reduce weight and increase run time. This allowed for a reconfiguration to four batteries in a series-parallel setup and an expected run time of over 30 minutes.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Motor 1</th>
<th>Motor 2</th>
<th>Motor 3</th>
<th>Motor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>2 stage</td>
<td>3 stage</td>
<td>2 stage</td>
<td>2 stage</td>
</tr>
<tr>
<td>Suction (inH20)</td>
<td>86</td>
<td>137</td>
<td>113.4</td>
<td>104.6</td>
</tr>
<tr>
<td>Volts</td>
<td>36</td>
<td>36</td>
<td>120</td>
<td>240</td>
</tr>
<tr>
<td>Amps</td>
<td>17.7</td>
<td>17.9</td>
<td>9</td>
<td>5.5</td>
</tr>
<tr>
<td>Weight (lbs.)</td>
<td>10</td>
<td>7</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>Cost (each $)</td>
<td>586</td>
<td>92</td>
<td>150</td>
<td>216</td>
</tr>
</tbody>
</table>

Fig. 3.5: Vacuum motor selection

**Backpack Shell**

An outer shell on the outside of the backpack was needed to isolate and contain the noise generated from the vacuum motor impellers. Several shelled backpack were available, but none could seal air-tight, nor were they a geometrical fit for the vacuum motors and batteries. The backpack trade study showed that the best method was to build the shell in house. Further design criteria can be found in Fig 3.6.
Noise Reduction Material

To reduce sound further, a device was needed to either absorb or cancel unwanted noise. The complexity of active noise cancellation was beyond the scope of this project. Sound absorbing material was employed to achieve the required 20 dB sound reduction. A trade study for the sound absorbing material used in the inner backpack shell is shown in Fig 3.7. Convoluted acoustic foam was chosen to line the inside of the backpack shell. This material met the 20 dB reduction requirement. Additional material studies for other various components can be found in Appendix B.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Product 1</th>
<th>Product 2</th>
<th>Product 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acoustic Foam</td>
<td>Wall Blanket</td>
<td>Eggcrate Foam</td>
</tr>
<tr>
<td></td>
<td>(convoluted)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (lbs./ft³)</td>
<td>1.5</td>
<td>0.25</td>
<td>1.2</td>
</tr>
<tr>
<td>Cost ($/ft²)</td>
<td>2.14</td>
<td>4.5-6</td>
<td>0.825 or 1.175</td>
</tr>
<tr>
<td>Thickness (in)</td>
<td>1 or 2</td>
<td>1.5 or 2.5</td>
<td></td>
</tr>
<tr>
<td>Max Temp. (°F)</td>
<td>250</td>
<td>250+</td>
<td>250</td>
</tr>
<tr>
<td>Noise Reduction Coefficient (NRC)</td>
<td>0.7 or 0.8</td>
<td>0.7</td>
<td>0.45 or 0.6</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Easy to cut and</td>
<td>Difficult to</td>
<td>Easy to cut and</td>
</tr>
<tr>
<td></td>
<td>shape</td>
<td>manipulate</td>
<td>shape</td>
</tr>
</tbody>
</table>

Fig. 3.7: Sound absorbing material selection
### 3.1.2 FEA Results

In order to determine if the PVAC components could withstand the required loads, several FEA studies were conducted to show the PVAC systems structural integrity. In each study, the worst-case scenario was examined to ensure no failure could occur during climbing. These studies were analyzed using the SolidWorks™ FEA solver. Each structural member used standard 3D ten-node tetrahedrals to conform to the complex geometry. Mesh refinements were iterated until stresses converged. The components of concern are listed below:

- The Aluminum Base
- The Handle
- The Foot Binding Baseplate

#### FEA of Aluminum Base

In order to verify that a material is going to hold up against any given load condition, a safety factor must be assessed. A safety factor greater than one, compared to a material’s yield strength, must be obtained to make sure it will not fail. Typical safety factors for structural components range from 1.5-2. Eq. 3.1 shows the basic variables used to find this safety factor for any isotropic material.

\[
  n_{safe} = \frac{Y_{yield}}{\sigma_{vM}} \quad (3.1)
\]

where von Mises Stress is given by Eq. 3.2

\[
  \sigma_{vM} = \sqrt{\frac{1}{2}[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)]} \quad (3.2)
\]

The model of interest was the assembly of the aluminum base and the handle. Fixed boundary conditions were applied around the flange (outer edge of pad). A vacuum pres-
ure of 3.5 psi was simulated by applying pressure to the inner concaved section of the pad assembly. Finally, a 300-lb. vertical force was applied to the area where a climber’s hand would grip. According to the FEA results, the maximum von Mises stress appeared around the bottom bolt hole region. This maximum stress value was roughly 23,500 psi. Yield strength for aluminum 5052-H32 is approximately 28,000 psi which gave a safety factor of 1.2. Fig 3.8 illustrates these values and the displacements within the pad.

*Note* - Safety factor of the pad is actually higher as aluminum 5052-H32 gets strain hardened when metal spun. Actual material properties could not be calculated for this strain hardening, so original 5052-H32 properties were used as a worst case in FEA. In addition, washers could not be added in the test model. Washers help distribute stresses more evenly at bolt hole regions, which would have lowered the stress value at each bolt hole region.

![Image](image.png)

Fig. 3.8: (a) Displacements within the pad, (b) Maximum von Mises stress \(\approx 23,500\text{psi}\)

**FEA of Handle**

The next component of concern was the handle. This redesigned handle implements ABS plastic posts with the grip section being 1” nominal aluminum pipe (6061). A worst-case scenario was investigated to see if one handle could withstand a 300 lb. vertical load. Each post was assumed bolted/clamped to the pad. A 300-lb load was applied to the
aluminum grip section. Fig 3.9 shows the stresses and displacements within the handle.

![Fig. 3.9: (a) Displacements within the handle, (b) von Mises stresses within the handle](image)

Since this analysis was done in assembly mode, a visual inspection of stresses from a color-coded chart was used for the aluminum grip and ABS posts. It appeared that slight yielding occurred around the edge regions of the ABS post. This proved not to be the case as the ABS handled the given loads in several weight tests conducted on the pads. The handle was loaded in both in the vertical (300-lb.) and horizontal (400-lb.) direction while testing the static coefficient of friction. Tests results showed no sign of yielding or cracks within the ABS posts. This suggested that FEA greatly aids you in design, but does not always predict stresses accurately.

*Note - Results are worst-case scenarios and do not reflect “typical” climbing conditions. Additional FEA information can be found in Appendix A.2

**FEA of Foot Binding Baseplate**

Another worst-case scenario was conducted on the aluminum plate that attaches to the bottom of the cable tightening foot bindings. The assumptions used for this component were 300-lbs. of force pulling upwards on the region were the polyester webbing is attached. Clamped conditions were then applied to the contact region of the binding and plate.
showing the FEA results are shown in Fig 3.10. The safety factor for this given model was about 1.3. Additional FEA results showing other scenarios can be found in Appendix A.4.

![FEA Results](image)

Fig. 3.10: (a) Displacement with full weight applied, (b) von Mises stresses with full weight applied

### 3.2 Ergonomic Enhancements

When climbing with the PVAC, human factors had to be addressed to improve the climbing mechanics. The original model of the PVAC was flawless when it came to climbing speed, but there were issues with that design. One of these issues was that the design caused premature fatigue, which translated in lower climbing endurance. In some cases painful muscle aches occurred. An illustration of muscle strength (fatigue) versus endurance (time) is found in Fig 3.11 [2, pg. 91]. The figure shows that, strength depletes exponentially over time. This depletion can be a result of too much weight, ergonomic factors, etc.

![Muscle Fatigue](image)

Fig. 3.11: Muscle fatigue over time
To improve upon human fatigue factors and fix issues in climbing mechanics, a reexamination of ergonomics was done in the following areas:

- Handle Design and Location
- Foot Accommodations
- Interface Connections
- Vacuum Pressure Release Mechanics

3.2.1 Handle Design and Location

After climbing several times with the PVAC system, it was decided that a new handle was necessary. When climbing for several minutes with the original handle, the climber’s forearm began to cramp. A reason for the “cramping” was that the handle was not located at the pads center of mass. This caused the climber’s arm to constantly fight a “bending moment.” After several minutes, fatigue kicked in and the forearm began to strain and ache. Another flaw in the original handle design was that it did not always have sufficient clearance between the handle and the aluminum base. This problem was more common with people who had larger hands, or those wearing gloves when climbing. This caused pinching on the fingers and was painful to the climber.

Research was conducted to improve the handle design and to address and eliminate these concerns. Several ergonomic dimension and factors suggested by Cacha, Kroemer, and Radwin [1–3] were used to redesign and build a new handle. Such parameters included using a diameter of 1.25 inches, using anthropometric dimensions of the hand to obtain sufficient clearance and avoid pinching, etc. An example of these implemented factors is shown in Fig 3.12. This newly configured handle is located at the center of the pad. By placing the handle at the center (center of mass), the climber’s forearm does not have to fight the constant bending from the undistributed weight of the pad itself. This relieves strain buildup in the climber’s forearm. Grips for the handle were also added to prevent
loss of circulation in the hands and to prolong climbing time.

![Handle with clearance added](image)

Fig. 3.12: Handle with clearance added

### 3.2.2 Foot Accommodations

Questions to ask when designing features for securing the feet are:

(a) Does it feel comfortable around the foot?

(b) Is it easy to slip the foot in and out?

(c) Does it securely lock in the foot?

The original version satisfied questions (a) and (b), but lacked in a method to securely lock the foot in place. To improve and enhance the design, cable tightening snowboard bindings were used. They are very easy to access and are known for their superb foot locking capabilities. The climber simply ratchets down on the foot to the proper tightness, and pulls up on cable tightening tab. The climber’s foot is securely locked into place. In addition, it eliminates the hassle needing a second person to assist the climber. The bindings not only implement good use of foot strength, but also use the ankle and heel. When secured, the cable tightening tab forms a triangle between the foot, ankle and heel that allows for efficient energy transfer within the foot. Getting out of the bindings is just as easy getting in them. The user simply pulls down on the cable tab and pulls up on the ratchet release tabs. Another benefit from using these bindings is that they can also be
adjusted for multiple shoe sizes and widths of the foot. Displayed in Fig 3.13 are pictures of the foot bindings in open and locked positions. These foot bindings are then fastened to a left and right aluminum baseplate. Each baseplate has three slotted areas on the left and right side, on which three polyester webbing sections can be sewn. These polyester pieces are sewn into one loop near the top of each binding to connect to each adjustable foot connection as shown in Fig 3.14.

Fig. 3.13: (a) Bindings in the open position, (b) Bindings in the locked position

Fig. 3.14: Foot binding with connection

3.2.3 Interface Connections

Another issue that arose from the many climbs was that the connecting material between the pads and foot support were too rigid and not adjustable. The earlier version
of the PVAC utilized fiberglass rebar sections to support a climber. Failures occurred numerous times when new climbers tried to move their feet without lifting the pads. This developed high bending stresses in the rods, and ultimately led to failure in some. To eliminate this weakness, a new material was selected that could withstand bending and flexing in any direction. Another favorable attribute of this new material was that it could be easily adjusted to accommodate the height of any individual. These benefits were achieved by selecting polyester webbing as the new material. Webbing is a fabric that is high in tensile strength, easily adjustable via cam locks, and bends and flexes without rip a or tear. An image illustrating this material is shown in Fig 3.3.

### 3.2.4 Vacuum Pressure Release Mechanics

The mechanics of the vacuum pressure release were reevaluated again to determine if there was a better method to release the vacuum. A first iteration was to see if the vacuum pressure release could be consolidated within the handle. This idea was deemed too difficult in design and manufacturing and was scraped. The next concept was to implement the thumb release. This proved to be an easier and more fatigue resistant method, as the thumb is the strongest finger [2, pg. 113]. One issue to be addressed with this concept was that dimensions were too lax at the bolt hole region. This caused jamming when the vacuum pressure release was under vacuum. To solve this issue, tolerances were tightened and a rubberized piece was added around the vacuum hole to aid in sealing. After those changes, the mechanics of the vacuum pressure release began operating smoothly.

### 3.3 Manufacturing Ease and Cost Estimation

Since manufacturing is necessary for any design, it is important to select the best possible manufacturing techniques. By selecting the proper manufacturing procedures, minimal build and assembly time is accomplished. This translates to lower cost production per part and a lower system cost overall. Some of the basic Design for Manufacturing and Assembly (DFMA) aids and tools are listed below:
• Part Consolidation

• Review of Manufacturing Techniques

• Determining Cost of Multiple n Number of Systems

3.3.1 Part Consolidation

The first step in improving the design was to reevaluate the current model and assess where parts could be consolidated. Boothroyd [4, pg. 82] outlined criteria to determine if parts could be consolidated and minimized. These considerations included:

• During the normal operating mode of the product, the part moves relative to all other parts already assembled (small motion does not apply)

• The part must be made of a different material, or be isolated from all other parts assembled (for insulation, vibrational dampening, etc.)

• The part must be separate from all other assembled parts, otherwise, the assembly of parts meeting one of the preceding criteria would be prevented

These steps were used to simplify regions such as the foot support. Instead of using several sections of fiberglass rebar, an adjustable and continuous piece of polyester webbing was used to simply this connection as shown in Figs 3.3, 3.14 and 3.15.

Fig. 3.15: Example of part consolidation
3.3.2 Review of Manufacturing Techniques

A review of the manufacturing techniques used to build the PVAC was conducted. Several small changes were made, but the biggest improvement was in the manufacturing of the pads. The initial process required large amounts of machining. This was done by taking a block aluminum (6061-T6), and milling it to the original concaved shape, as shown in Fig 1.2 (b). To improve the existing manufacturing process, alternative methods of making thin walled structures were investigated. Metal stamping was first assessed to see if that option was viable. Metal stamping takes a preshaped piece of sheet metal, and holds it into place using hydraulic clamps. This metal is then pressed into the designated die shape using a set of hydraulic pistons. This option proved to be undesirable because of the high cost of producing the die. While investigating other methods, “metal spinning” was discovered.

Description of Metal Spinning

Metal spinning is a process used to manufacture basic cylindrical pots and pans. It takes advantage of axisymmetry to form parts around a pre-designed mandrel positioned on a lathe. First, the pre-sized blank is clamped via a pressure pad to the spinning mandrel and tailstock. The lathe is then turned up to the proper “spinning” speed. An operator or CNC program then uses a roller tool to press the blank into the mandrel. This causes the metal to flow into the desired shape and size. Fig 3.16 illustrates the process of metal spinning. Because of this procedure, the machined piece is cold worked (strain hardened), causing material properties to alter and improve. The actual mandrel used to produce the pads is shown in Fig 3.17.
Fig. 3.16: (a) Part being metal spun, (b) Depiction of metal spinning tools and equipment

Fig. 3.17: (a) Front of mandrel, (b) Back on mandrel
A updated process selection is shown below in Fig 3.18.

![Table showing process selection](image)

**Fig. 3.18: Process trade study**

### 3.3.3 Determining Cost of Multiple $n$ Number of Systems

To assess the cost of producing multiple $n$ number of systems, several steps were taken. The first step was to record the cost of each component to form a bill of materials (found in Appendix G). The bill of materials is a list of each part number, a small description of each part, its weight, cost, and the part supplier. After the bill of materials was established, equipment cost was factored in. This included all the necessary tools to assemble each part, such as software, actual tools, epoxy, etc. Next, labor cost had to be established. The initial time to build the PVAC was lengthy and tedious. This was due to inexperience in building the new PVAC system and not using the best or proper shop tools. According to Boothroyd [4, pp. 123-126], a learning curve can be established on components, which reduces the assembly time by upwards of 90% for large productions. For cost estimation purposes, the first system was used to calculate the initial time to build and assemble the PVAC system. The cost estimation to build five systems assumed that a 50% learning was obtained and labor time was cut in half. Cost estimations for seven built systems assumed
a 60% learning and 40% of original labor time was used. Below is a summary of these cost estimations shown in Tables 3.1, 3.2, 3.3, 3.4 and 3.5. Labor cost estimations are shown in Table 3.6.

Table 3.1: Cost and Weight Contributions - Batteries

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost</th>
<th>% Contribution</th>
<th>Weight (lbs)</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pad Subsystem</td>
<td>$535.29</td>
<td>23.84%</td>
<td>8.38</td>
<td>16.69%</td>
</tr>
<tr>
<td>Foot Support Subsystem</td>
<td>$222.60</td>
<td>9.91%</td>
<td>7.50</td>
<td>14.95%</td>
</tr>
<tr>
<td>Safety Subsystem</td>
<td>$285.65</td>
<td>12.72%</td>
<td>3.20</td>
<td>6.38%</td>
</tr>
<tr>
<td>Backpack Subsystem</td>
<td>$1,201.82</td>
<td>53.52%</td>
<td>31.10</td>
<td>61.98%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,245.36</strong></td>
<td><strong>100%</strong></td>
<td><strong>50.18</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Table 3.2: Cost and Weight Contributions - Converter

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost</th>
<th>% Contribution</th>
<th>Weight (lbs)</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pad Subsystem</td>
<td>$535.29</td>
<td>16.24%</td>
<td>8.38</td>
<td>18.58%</td>
</tr>
<tr>
<td>Foot Support Subsystem</td>
<td>$222.60</td>
<td>6.75%</td>
<td>7.50</td>
<td>16.64%</td>
</tr>
<tr>
<td>Safety Subsystem</td>
<td>$285.65</td>
<td>8.66%</td>
<td>3.20</td>
<td>7.10%</td>
</tr>
<tr>
<td>Backpack Subsystem</td>
<td>$2,253.46</td>
<td>68.35%</td>
<td>26.00</td>
<td>57.68%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$3,297.00</strong></td>
<td><strong>100%</strong></td>
<td><strong>45.08</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Table 3.3: Final Cost - Batteries Only

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>1 System</th>
<th>5 Systems</th>
<th>7 Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>$3,114.22</td>
<td>$11,226.80</td>
<td>$14,763.32</td>
</tr>
<tr>
<td>Tooling (Fixed)</td>
<td>$1,196.70</td>
<td>$1,246.70</td>
<td>$1,296.70</td>
</tr>
<tr>
<td>Labor</td>
<td>$404.55</td>
<td>$934.54</td>
<td>$1,042.33</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$4,715.47</strong></td>
<td><strong>$13,408.04</strong></td>
<td><strong>$17,102.35</strong></td>
</tr>
<tr>
<td>For (1) System</td>
<td><strong>$4,715.47</strong></td>
<td><strong>$2,681.61</strong></td>
<td><strong>$2,443.19</strong></td>
</tr>
</tbody>
</table>

Table 3.4: Final Cost - Converters Only

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>1 System</th>
<th>5 Systems</th>
<th>7 Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>$4,373.10</td>
<td>$16,485.00</td>
<td>$22,066.18</td>
</tr>
<tr>
<td>Tooling (Fixed)</td>
<td>$1,196.70</td>
<td>$1,246.70</td>
<td>$1,296.70</td>
</tr>
<tr>
<td>Labor</td>
<td>$404.55</td>
<td>$934.54</td>
<td>$1,042.33</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$5,974.35</strong></td>
<td><strong>$18,666.24</strong></td>
<td><strong>$24,405.21</strong></td>
</tr>
<tr>
<td>For (1) System</td>
<td><strong>$5,974.35</strong></td>
<td><strong>$3,733.25</strong></td>
<td><strong>$3,486.46</strong></td>
</tr>
</tbody>
</table>
Table 3.5: Final Cost - Both Systems Considered

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>1 System</th>
<th>5 Systems</th>
<th>7 Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>$4,730.85</td>
<td>$18,273.75</td>
<td>$24,570.43</td>
</tr>
<tr>
<td>Tooling (Fixed)</td>
<td>$1,196.70</td>
<td>$1,246.70</td>
<td>$1,296.70</td>
</tr>
<tr>
<td>Labor</td>
<td>$404.55</td>
<td>$934.54</td>
<td>$1,042.33</td>
</tr>
<tr>
<td>Total</td>
<td>$6,332.10</td>
<td>$20,454.99</td>
<td>$26,909.46</td>
</tr>
<tr>
<td>For (1) System</td>
<td>$6,332.10</td>
<td>$4,091.00</td>
<td>$3,844.21</td>
</tr>
</tbody>
</table>
Table 3.6: Labor Cost Breakdown

<table>
<thead>
<tr>
<th>Process</th>
<th>Metal Spinning</th>
<th>Machining of Pad</th>
<th>Assembly of Pad</th>
<th>Cutting of Aluminum Plate</th>
<th>Sewing Operations</th>
<th>Backpack Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate ($/hr)</td>
<td>20</td>
<td>20</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Time (Hours)/One System</td>
<td>0.367</td>
<td>1.367</td>
<td>2.5</td>
<td>1.083</td>
<td>4.29</td>
<td>15</td>
</tr>
<tr>
<td>Time (Hours)/Five System</td>
<td>0.533</td>
<td>1.500</td>
<td>6.25</td>
<td>1.167</td>
<td>10.71</td>
<td>37.5</td>
</tr>
<tr>
<td>Time (Hours)/Seven System</td>
<td>0.600</td>
<td>1.567</td>
<td>7</td>
<td>1.200</td>
<td>12.00</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total Cost/One System</th>
<th>$ 7.33</th>
<th>$ 27.33</th>
<th>$ 37.50</th>
<th>$ 21.67</th>
<th>$ 85.71</th>
<th>$ 225.00</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Cost/Five Systems</td>
<td>$ 10.67</td>
<td>$ 30.00</td>
<td>$ 93.75</td>
<td>$ 23.33</td>
<td>$ 214.29</td>
<td>$ 562.50</td>
</tr>
<tr>
<td></td>
<td>Total Cost/Seven Systems</td>
<td>$ 12.00</td>
<td>$ 31.33</td>
<td>$ 105.00</td>
<td>$ 24.00</td>
<td>$ 240.00</td>
<td>$ 630.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total Labor Cost/One System</th>
<th>$ 404.55</th>
<th>$ 404.55</th>
<th>Labor Cost/System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Labor Cost/Five Systems</td>
<td>$ 934.54</td>
<td>$ 186.91</td>
<td>Labor Cost/System</td>
</tr>
<tr>
<td></td>
<td>Total Labor Cost/Seven Systems</td>
<td>$ 1,042.33</td>
<td>$ 148.90</td>
<td>Labor Cost/System</td>
</tr>
</tbody>
</table>
As the preceding tables and figure indicate, there is a big price difference between building one system, and building five, or even seven. The difference in price is contributed to:

- Buying in bulk
- Decreased labor cost
- Fixed tooling cost
- Geometric optimization

Geometric optimization is a major factor in lowering costs, since increasing the size of aluminum sheet for a certain number of parts minimizes part costs and decreases scrap waste. Labor cost is strongly influenced by the learning curve and using proper machinery for each individual operation.

3.4 Failure Modes and Effects Analysis

To ensure a safe PVAC system, Failure Modes and Effects Analysis was considered. When using FMEA, each individual component is examined. The severity and likelihood of failure is then determined through testing or knowledge of previous failures. For this project, a FMEA was done using the following steps:

- Identifying the hazard
- Listing the possible causes
- Determining the effects
- Assessing an initial Risk Priority Code (RPC)
- Applying countermeasure or detection tools to mitigate failure
- Determining a final Risk Priority Code (RPC)
Fig 3.19 shows FMEA for the PVAC II system. Following this figure, the severity and probability of failure for each component is assessed, followed by the Risk Assessment Matrix.
<table>
<thead>
<tr>
<th>Hazard</th>
<th>Cause</th>
<th>Effect</th>
<th>RPC</th>
<th>Countermeasures</th>
<th>RPC After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter(s) Failure *</td>
<td>Exposed to high temperature environment or disconnection</td>
<td>Loss of suction to one or both pads</td>
<td>2</td>
<td>Test converter(s) before climb</td>
<td>3</td>
</tr>
<tr>
<td>Unplugging of power cord</td>
<td>Insufficient tension relief in power cord</td>
<td>Complete loss of suction to system</td>
<td>2</td>
<td>Use a belay line if necessary</td>
<td>3</td>
</tr>
<tr>
<td>PWMI Failure *</td>
<td>PWM burns up or shorts out</td>
<td>Loss of suction to one or both pads</td>
<td>1</td>
<td>Add tension relief to electrical cords</td>
<td>3</td>
</tr>
<tr>
<td>Batteries discharge beyond minimum capacity *</td>
<td>Batteries discharge pass “point of no return”</td>
<td>Complete loss of suction to system</td>
<td>2</td>
<td>Climb with portable power source (Batteries)</td>
<td>3</td>
</tr>
<tr>
<td>*Batteries explode</td>
<td>Short in battery connection</td>
<td>Complete loss of suction to system</td>
<td>2</td>
<td>Test PWM connections and visually inspect fuse</td>
<td>3</td>
</tr>
<tr>
<td>Vacuum motor burns out/Impeller Failure *</td>
<td>Debris caught in vacuum motor</td>
<td>Loss of suction to one or both pads</td>
<td>1</td>
<td>Use a belay line if necessary</td>
<td>3</td>
</tr>
<tr>
<td>Foot Support Failure *</td>
<td>Polyester webbing on foot supports get cut while climbing</td>
<td>Unable to climb with one or both feet</td>
<td>2</td>
<td>Check voltage levels in batteries before climb</td>
<td>3</td>
</tr>
<tr>
<td>Pressure Release Failure *</td>
<td>Pressure release(s) break while climbing</td>
<td>Unable to operate pad(s)</td>
<td>2</td>
<td>Visual inspection of fraying in polyester webbing before climbing the wall</td>
<td>3</td>
</tr>
<tr>
<td>Vacuum/Voltmeter Gauge Failure *</td>
<td>Gauges break or are inoperable during climb</td>
<td>Can’t reference vacuum pressure or voltage</td>
<td>2</td>
<td>Check for weakness in pressure releases before climb</td>
<td>3</td>
</tr>
</tbody>
</table>

*Warfighter ties rope to existing suction pad and rapels down

Fig. 3.19: FMEA of the PVAC II system
Risk Assessment:

Suction Pad:

- **Loss of Suction (1 pad)**
  - (severity-III, probability-C)
- **Loss of Suction (2 pads)**
  - (severity-I, probability-D)
  - Warfighter will fall
- **Skirt Failure**
  - (severity-I, probability-E)
- **Loss of Friction**
  - (severity-I, probability-D)
  - Search for another route
  - Stop and repel or climb down
- **Vacuum Gauge Failure**
  - (severity-IV, probability-E)
  - Reference voltmeter for estimated suction
  - Test suction before applying weight
- **Voltmeter Failure**
  - (severity-IV, probability-D)
  - Continue to climb referencing the vacuum gauge
- **Pressure Release Valve Failure**
  - (severity-I, probability-D)
  - Operate manually if possible
- **Pulse Width Modulator Failure**
  - (severity-I, probability-D)

Vacuum Motor:

- **Motor Burns Out**
  - (severity-I, probability-D)
- **Impeller Failure**
  - (severity-I, probability-D)

Foot Support:

- **Foot Support Failure**
  - (severity-I, probability-E)

Batteries:

- **Batteries Discharged Beyond Minimum Capacity**
  - (severity-I, probability-E)
- **Short in the Wiring**
  - (severity-I, probability-D)
- **Batteries Explode**
  - (severity-I, probability-E)
  - Ensure the lid on container is secure
  - Remove motor mounts and assembly from pack

Converter:

- **Unplugging due to insufficient tension relief**
  - (severity-I, probability-E)
- **Short in the Wiring**
  - (severity-I, probability-D)

*Warfighter ties rope to existing suction pad and repels down*
### RISK ASSESSMENT MATRIX

<table>
<thead>
<tr>
<th>Category</th>
<th>Descriptive Word</th>
<th>Potential Consequences</th>
<th>PROBABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Personnel Injury/Illness</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>I</td>
<td>Catastrophic</td>
<td>Fatality or Permanent disability</td>
<td>Frequent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Regulatory non-compliance and immediate danger to environment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Release not captured prior to compliance point with biological impact</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Remedial actions &gt; 1 year or &gt;$250,000</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Critical</td>
<td>Severe injury, Severe occupational illness</td>
<td>Frequent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Release in excess of quantity reportable (RQ) to NRC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Release not captured prior to compliance point with biological impact</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Remedial actions 1 – 12 months or $10,000 - $250,000</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Marginal</td>
<td>Minor injury, minor occupational illness</td>
<td>Frequent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Release of non reportable quantity, captured prior to compliance point</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Remedial actions 1 – 31 days or $5,000 - $10,000</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Negligible</td>
<td>Less Than minor injury or illness</td>
<td>Frequent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- No Federal or State permit violations</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Release contained at site of release</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Remedial action &lt; 1 day or &lt;$5,000</td>
<td></td>
</tr>
</tbody>
</table>
### PROBABILITY

<table>
<thead>
<tr>
<th>Level</th>
<th>Descriptive Word</th>
<th>Definition</th>
<th>1 Failure in # Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Frequent</td>
<td>Likely to occur repeatedly during the life cycle of the system (test/activity/operation)</td>
<td>&lt;10</td>
</tr>
<tr>
<td>B</td>
<td>Reasonably Probable</td>
<td>Likely to occur several times during the life cycle of the system (test/activity/operation)</td>
<td>10 - 99</td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
<td>Likely to occur sometime during the life cycle of the system (test/activity/operation)</td>
<td>100 - 999</td>
</tr>
<tr>
<td>D</td>
<td>Remote</td>
<td>Not likely to occur during the life cycle of the system (test/activity/operation)</td>
<td>1000 - 999999</td>
</tr>
<tr>
<td>E</td>
<td>Extremely Improbable</td>
<td>Probability of occurrence cannot be distinguished from zero</td>
<td>1M – 100M</td>
</tr>
<tr>
<td>F</td>
<td>Impossible</td>
<td>Physically impossible to occur</td>
<td>0 Failures/∞ cycles</td>
</tr>
</tbody>
</table>

### RISK PRIORITY CODE (RPC)

<table>
<thead>
<tr>
<th>Code</th>
<th>Risk</th>
<th>Contractor Action Required</th>
<th>Air Force Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High</td>
<td>Imperative to suppress risk to lower level before operation</td>
<td>Imperative to lower risk if possible, approval required</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
<td>Operation may require written, time limited waiver endorsed by Air Force and participating contractors</td>
<td>Approval required as applicable</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Operation permissible</td>
<td>None</td>
</tr>
</tbody>
</table>
Chapter 4

Testing

The following tests were conducted to validate or update preexisting data:

- Sound Reduction
- Battery Voltage Profile
- Temperature Analysis
- Vacuum Motor Performance
- Weight Testing
- Friction Coefficient Experiments

4.1 Sound Reduction

Reducing noise was a main concern for this project. Sound measurements needed to be determined for the original PVAC system, and the new system. Testing took place in an anechoic chamber, which meant no environmental sound interference. The vacuum motors were turned on and measurements were taken at several locations around the backpack system to establish which location was loudest. Table 4.1 shows that the noisiest positions were measured above and below the vacuum motors. The averaged decibel rating for the original PVAC system was 91.6 dB.
Table 4.1: Average sound readings of old system when vacuum pressure release is closed

<table>
<thead>
<tr>
<th>Sound Level (dB)</th>
<th>Back</th>
<th>Bottom</th>
<th>Right</th>
<th>Top</th>
<th>Left</th>
<th>Front</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Averages</td>
<td>92</td>
<td>93</td>
<td>89.2</td>
<td>93</td>
<td>92.4</td>
<td>90</td>
<td>91.6</td>
</tr>
</tbody>
</table>

After passive noise cancellation methods were applied to the system, the same test conditions were used to determine the overall sound reduction. Table 4.2 shows the average values at several locations around the backpack system. The overall average decibel rating for this system was 70.9 dB.

Table 4.2: Average sound readings of new system when vacuum pressure release is opened and closed

<table>
<thead>
<tr>
<th>Sound Level (dB)</th>
<th>Back</th>
<th>Bottom</th>
<th>Right</th>
<th>Top</th>
<th>Left</th>
<th>Front</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suctioned</td>
<td>69.8</td>
<td>75.5</td>
<td>67.6</td>
<td>68.7</td>
<td>70.4</td>
<td>69.8</td>
<td>70.3</td>
</tr>
<tr>
<td>Open</td>
<td>73</td>
<td>77.3</td>
<td>68</td>
<td>70.7</td>
<td>70.7</td>
<td>70.4</td>
<td>71.7</td>
</tr>
<tr>
<td>Average</td>
<td>71.4</td>
<td>76.4</td>
<td>67.8</td>
<td>69.7</td>
<td>70.5</td>
<td>70.1</td>
<td>71</td>
</tr>
</tbody>
</table>

A graph showing the average differences in decibels between the old and new system is shown in Fig 4.1. The new passive system reduced the noise by over 20 dB in all directions satisfying the design requirement.

![Fig. 4.1: Average dB’s of old and new system](image-url)
4.2 Battery Voltage Profile

Since there was a change in battery setup, another voltage profile needed to be established. The test lasted until the batteries reached a maximum discharge state. As shown in Fig 4.2, the minimum voltage before motor shutoff occurred was 30 volts. Significant voltage drop transpired after the 30-minute mark. This timing mark also proved to be a minimum point to safely hold 300-lbs.

![Battery Voltage Profile](image)

Fig. 4.2: Profile of batteries in series-parallel setup

4.3 Temperature Analysis

Temperature measurements were taken while the following major components were operating:

- Vacuum Motors
- Batteries
- Pulse Width Modulators (PWM)
- AC to DC Converters

In the first iteration of this test, LiPo batteries were used. Climbing conditions were simulated by sucking down the pads for five seconds and then releasing air for five seconds. Several thermocouples were attached to the vacuum motor, batteries, and the PWM. Results
were recorded for the lifetime of the batteries. Temperature profiles of the test locations are listed in Fig 4.3.

*Note* - Thermocouple accuracy is ±2°C

Next, testing of the inverter was analyzed. The same conditions were applied: sealing and releasing at five second intervals. Thermocouples were placed on the vacuum motors, converter, and PWM. From previous testing, the converter had to be placed outside of the sound-proof box due to overheating and thermal shutdown. The test was conducted for 33.5 minutes. As Fig 4.4 shows, steady state temperatures occurred around 18-20 minutes (1080-1200 seconds).
4.4 Vacuum Motor Performance

A test was performed to assess whether the vacuum motors met the prescribed specifications. Voltage, current, and vacuum pressure were recorded, (as shown in Fig 4.5) and graphs of “Voltage vs. Current” (Fig 4.6), “Current vs. Suction” (Fig 4.7), and “Voltage vs. Suction” (Fig 4.8) were created. Shown below are the data collected and the graphs:

<table>
<thead>
<tr>
<th>Voltage (Volts)</th>
<th>Current (amps)</th>
<th>Suction (in H2O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>15.0</td>
<td>8.4</td>
<td>16.0</td>
</tr>
<tr>
<td>20.2</td>
<td>9.4</td>
<td>28.0</td>
</tr>
<tr>
<td>25.3</td>
<td>10.5</td>
<td>39.0</td>
</tr>
<tr>
<td>30.5</td>
<td>11.34</td>
<td>49.0</td>
</tr>
<tr>
<td>32.0</td>
<td>11.8</td>
<td>54.0</td>
</tr>
<tr>
<td>33.2</td>
<td>12.0</td>
<td>56.0</td>
</tr>
<tr>
<td>35.6</td>
<td>12.6</td>
<td>59.0</td>
</tr>
<tr>
<td>37.0</td>
<td>13.1</td>
<td>60.0</td>
</tr>
<tr>
<td>38.5</td>
<td>12.8</td>
<td>65.0 (reset pad)</td>
</tr>
<tr>
<td>39.3</td>
<td>12.9</td>
<td>66.0</td>
</tr>
<tr>
<td>40.6</td>
<td>13.1</td>
<td>68.0</td>
</tr>
<tr>
<td>41.7</td>
<td>13.3</td>
<td>70.0</td>
</tr>
<tr>
<td>45.4</td>
<td>15.6</td>
<td>77.0 (reset pad)</td>
</tr>
<tr>
<td>46.1</td>
<td>14.5</td>
<td>80.0</td>
</tr>
<tr>
<td>48.3</td>
<td>15.3</td>
<td>83.0</td>
</tr>
</tbody>
</table>

Fig. 4.5: Vacuum data
Fig. 4.6: Current vs Voltage

Fig. 4.7: Suction vs Current
The testing indicated that the vacuum motors met all of the specifications except the vacuum pressure (in $H_2O$). The manufacturer’s website claimed 147 in $H_2O$ at 36 VDC, but testing yielded a vacuum pressure of about 65-70 in $H_2O$. An additional 10 in $H_2O$ might have been obtained if the system was perfectly sealed but that would still be nowhere near the stated 147 in $H_2O$. This false claim could have been from mislabeling, incorrect units, etc. This testing was very beneficial as it allowed in alteration of the system design before problems occurred. For example, if the pads size were kept as small as originally designed, the system would not have been able to hold the required 300-lb. vertical load.

4.5 Friction Coefficient Experiments

This section will be divided into the following subsections:

- Rubber Mechanics
- Horizontal Testing and Results
- Vertical Testing and Results
- Static Coefficient of Friction
4.5.1 Rubber Mechanics

According to Smith [5], static friction is defined as "friction developed at the contacting interface of an elastomeric material and a paired solid, one element of which is applying a tangent force to the other, but no sustained relative movement between them occurs". Our surfaces of concern are the Mi6 Stealth® rubber and the opposing contacting surface. Rubber does not follow the standard metallic friction equation. Mechanics of rubber include bulk deformation hysteresis, van der Waals’ adhesion between paired surfaces, and cohesion loss contribution from rubber wear [5, pg. 30]. This theorized total resistive force encompassing the mechanics described above is shown in Eq 4.1:

\[ F_t = F_A + F_{Hb} + F_C \]  \hspace{1cm} (4.1)

The standard equation for finding the static coefficient of friction is shown in Eq 4.2. This has been the standard equation used for most materials. For the special case of rubber in contact, Smith [5, pg. 221] suggested that the equation used to find the static coefficient of friction follows the generalized Hertz equation shown in Eq 4.3. As seen in the Hertz equation, the static coefficient of friction decreases with increasing normal force. This might not be intuitive, but Hertz derivation of adhesion forces between the paired surfaces results in a decreasing power function [5, pp. 22-24]. This equation proved to correlate well with the test data, as shown in the subsequent sections.

\[ \mu_{stat} = \frac{F_t}{F_N} \]  \hspace{1cm} (4.2)

\[ \mu_{stat} = c(F_N)^{-m} \]  \hspace{1cm} (4.3)

Further testing would be needed to find coefficients c and m.
4.5.2 Horizontal Testing and Results

To obtain the correlation between normal force \( (F_N) \) and vacuum pressure, a test was conducted to collect these data points. The setup was simply, a daisy chain (strap) connected from the center of the pad handle to a weight scale. This scale was then supported by an overhead crane. The PVAC was then engaged, sucking the pad onto a painted concrete surface. Force was applied by pulling on the chain that raised the crane/hoist. The failure load was then recorded for each increment of vacuum pressure (shown in Fig 4.9. The vacuum pressure range went from 5-55 in \( H_2O \) in increments of 5 in \( H_2O \).

![Horizontal testing setup](image)

Fig. 4.9: Horizontal testing setup

A graph representing these data points is shown in Fig 4.10. A linear fit was applied for these values and a least squares value of 0.9924 was obtained showing that pressure as a function of force is linear. This should be expected as the actual equation correlating
pressure and force is linear (Eq. 4.4)

\[ F_N = P_{\text{vac}}A_{\text{suct}} \]  \hspace{1cm} (4.4)

Fig. 4.10: Horizontal testing on a painted concrete floor

4.5.3 Vertical Testing and Results

In order to measure the static coefficient of friction, a series of test using tribometers must be conducted under ASTM standards. Unfortunately, this equipment could not be obtained through university resources that would measure to the large scale of the PVAC, so personal tests were conducted. Test equipment consist of a PVAC system with one pad, a daisy chain (strap), clamps, and a squat machine with safety locks. The tested surfaces consisted of:
• Unpainted OSB wafer board

• 1/4 " Acrylic Plexiglass

• 3/4" Acrylic Plexiglass

For each test, the boards were clamped into place at the corners. The daisy chain (strap) was connected from the safety ring (U-bolt) to the squat bar. The bar was lifted and the vacuum motors were turned on. The bar was gently lowered until the daisy chain (strap) supported it, letting the bar hang freely. Weights were then applied at each end of the squat bar. The PWM was slowly adjusted until sliding began. The “sliding” vacuum pressure was then recorded for the given weights applied. Fig 4.11 shows the setup for each test.

Fig. 4.11: (a) Daisy chain connecting from bar to pads, (b) Pad vacuumed to plexiglass (weights applied)

Results of the vertical tests are shown in Figs 4.12, 4.13, and 4.14. By plotting the coefficient of determination values($R^2$), it becomes apparent that the data points reflect the linear model.
Fig. 4.12: Vertical Testing - OSB Wafer Board Unpainted

Fig. 4.13: Vertical Testing - Plexiglass 1/4"
*Note* - As seen from the graphs above, the y intercept in the horizontal and some vertical graphs appear not to be at zero. Smith [5, pg. 102] suggested this offset could be attributed to adhesion and microhysteresis forces between the paired surfaces.

### 4.5.4 Static Coefficient of Friction Results

To correlate how well each model fits the Hertz equation (as stated in subsection 4.5.1), the static coefficient was determined by comparing vertical test data from each surface to the horizontal test data. Tables 4.3, 4.4, and 4.5 show these values.
Table 4.3: Static Coefficient of Friction - OSB Wafer Board

<table>
<thead>
<tr>
<th>Pressure (in H2O)</th>
<th>Horizontal (lbs)</th>
<th>Vertical (lbs)</th>
<th>$\mu_{stat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>110</td>
<td>125</td>
<td>1.13</td>
</tr>
<tr>
<td>25</td>
<td>139</td>
<td>146</td>
<td>1.05</td>
</tr>
<tr>
<td>30</td>
<td>186</td>
<td>150</td>
<td>0.81</td>
</tr>
<tr>
<td>35</td>
<td>211</td>
<td>192</td>
<td>0.91</td>
</tr>
<tr>
<td>40</td>
<td>233</td>
<td>210</td>
<td>0.90</td>
</tr>
<tr>
<td>45</td>
<td>276</td>
<td>231</td>
<td>0.84</td>
</tr>
<tr>
<td>50</td>
<td>291</td>
<td>250</td>
<td>0.86</td>
</tr>
<tr>
<td>55</td>
<td>315</td>
<td>274</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Table 4.4: Static Coefficient of Friction - Plexiglass 1/4"

<table>
<thead>
<tr>
<th>Pressure (in H2O)</th>
<th>Horizontal (lbs)</th>
<th>Vertical (lbs)</th>
<th>$\mu_{stat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>110</td>
<td>134</td>
<td>1.22</td>
</tr>
<tr>
<td>25</td>
<td>139</td>
<td>155</td>
<td>1.11</td>
</tr>
<tr>
<td>30</td>
<td>186</td>
<td>185</td>
<td>1.00</td>
</tr>
<tr>
<td>35</td>
<td>211</td>
<td>200</td>
<td>0.95</td>
</tr>
<tr>
<td>40</td>
<td>233</td>
<td>222</td>
<td>0.95</td>
</tr>
<tr>
<td>45</td>
<td>276</td>
<td>235</td>
<td>0.85</td>
</tr>
<tr>
<td>50</td>
<td>291</td>
<td>265</td>
<td>0.91</td>
</tr>
<tr>
<td>55</td>
<td>315</td>
<td>287</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Table 4.5: Static Coefficient of Friction - Plexiglass 3/4”

<table>
<thead>
<tr>
<th>Pressure (in H2O)</th>
<th>Horizontal (lbs)</th>
<th>Vertical (lbs)</th>
<th>$\mu_{stat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>27</td>
<td>4.57</td>
</tr>
<tr>
<td>10</td>
<td>33</td>
<td>45</td>
<td>1.36</td>
</tr>
<tr>
<td>15</td>
<td>68</td>
<td>73</td>
<td>1.09</td>
</tr>
<tr>
<td>20</td>
<td>110</td>
<td>97</td>
<td>0.88</td>
</tr>
<tr>
<td>25</td>
<td>139</td>
<td>120</td>
<td>0.86</td>
</tr>
<tr>
<td>30</td>
<td>186</td>
<td>145</td>
<td>0.78</td>
</tr>
<tr>
<td>35</td>
<td>211</td>
<td>155</td>
<td>0.74</td>
</tr>
<tr>
<td>40</td>
<td>233</td>
<td>189</td>
<td>0.81</td>
</tr>
<tr>
<td>45</td>
<td>276</td>
<td>212</td>
<td>0.77</td>
</tr>
<tr>
<td>50</td>
<td>291</td>
<td>235</td>
<td>0.81</td>
</tr>
<tr>
<td>55</td>
<td>315</td>
<td>258</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Graphs of static coefficient of friction versus normal force were then plotted using the Hertz model as suggested by Smith (Figs 4.15, 4.16, 4.17). When the data points derived from the friction tests are plotted over a graph of the Hertz model $R^2$ values, they look similar. Originally, the OSB wafer board had a lower $R^2$ value due to an outlier. This could have been an error attributed to visual inspection accuracies, improperly resetting the pad, insufficient sealing, rubber hysteresis, etc. This graph was changed to exclude the outlier in the Hertz model fit giving a much higher $R^2$ value.
Fig. 4.15: Static Coefficient of Friction vs Normal Force OSB

Fig. 4.16: Static Coefficient of Friction vs Normal Force Plexiglass 1/4”
4.5.5 Static Coefficient of Friction Conclusion

As a result of the static coefficient of friction testing, conclusions can be made about the safety of the climb by:

- Determining the climbers total weight (climbers weight and backpack weight)
- Determining the effective suction area of the pads (area in which vacuum pressure acts)
- Testing the vacuum motor on given surface to determine the operating pressure
- Using test results or looking up static coefficient of friction between rubber strips and wall surfaces

Once these variables have been determined, a safety factor can be established for vertical climbing using Eq 4.5:

\[
  n_{safe} = \frac{P_{vac}A_{suct} \mu_{stat}}{F_{climber}}
\]

This safety factor determines how safe it is to climb certain surfaces. Brick, glass, and concrete have been ideal surfaces to climb on. These surfaces have been either rough which
allows for good microhysteresis forces or have had very good adhesion forces. Other surfaces
with less rubber interaction would need to be tested to ensure safe climbing conditions.
Chapter 5

Conclusion

5.1 Summary

Several components changed with the new design of the PVAC system. Either these components were modified or a completely new material was selected. Table 5.1 summarizes these component changes and the improvements made from these changes. The overall improvements compared to the original system were:

- Decreased PVAC system weight by 10 lbs.
- Enhanced ergonomics and ease of climbing
- Improved manufacturing and assembly
- Cost to build one system reduced
- Increased time of operation greater than 30 minutes (batteries)
- Reduced sound level from 90 dB to 70 dB (20 dB reduction)
Table 5.1: PVAC Changes and Improvements

<table>
<thead>
<tr>
<th>Component</th>
<th>Change</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Base</td>
<td>Shape and size</td>
<td>Easier to manufacture/Weight reduction</td>
</tr>
<tr>
<td>Pad Handle</td>
<td>New design and location</td>
<td>Weight balance and ergonomic improvements</td>
</tr>
<tr>
<td>Vacuum Pressure Release</td>
<td>Location/Operates by thumb</td>
<td>Ergonomic improvements</td>
</tr>
<tr>
<td>Rubber Strips</td>
<td>New rubber selected</td>
<td>Improved static coefficient of friction</td>
</tr>
<tr>
<td>Foot Connection Straps</td>
<td>Material change</td>
<td>Ergonomic and manufacturing improvements</td>
</tr>
<tr>
<td>Foot Bindings</td>
<td>Alternative component</td>
<td>Ease of foot access</td>
</tr>
<tr>
<td>Vacuum Motors</td>
<td>120 VAC to 36 VDC Motors</td>
<td>Fewer batteries required- Weight reduction</td>
</tr>
<tr>
<td>Converters</td>
<td>External power source</td>
<td>Reduced likelihood of failure/Improved safety</td>
</tr>
<tr>
<td>Electrical Wire</td>
<td>More flexible wire</td>
<td>Added strain relief/Improved safety</td>
</tr>
<tr>
<td>Wiring Setup</td>
<td>Series to parallel series combination</td>
<td>Increased climbing time by 10 minutes +</td>
</tr>
<tr>
<td>Backpack Frame</td>
<td>Smaller frame chosen</td>
<td>Weight Reduction</td>
</tr>
<tr>
<td>Backpack Shell and Muffler</td>
<td>Encases batteries and vacuum motors</td>
<td>Passive noise cancellation</td>
</tr>
</tbody>
</table>
5.2 Applications

The PVAC II fulfilled the design requirements. Climbing mechanics were greatly enhanced by ergonomics, lighter weight, and ease of use. Lastly, sound reduction was greatly improved. Possible uses for the PVAC include:

- Military Applications
- Rescue Operations
- Recreational Use

5.2.1 Military Applications

Military applications could include fighting environments where climbing over large obstructions was necessary. Stealthy operations might also be used for Covert Operations.

5.2.2 Rescue Operations

Rescue tasks could include firefighting situations where accessing the interior of a building is not viable option or could be life threatening to the firefighter. Roofing operations could also use the PVAC for a temporary anchor point if the surface cannot be fastened to. The window washing industry might even be able to use the PVAC if it seemed feasible.

5.2.3 Recreational Use

For recreational use, the obvious use would be at a local rock climbing facility or a carnival. The PVAC could be sold to the public if proper standardized ASTM or OSHA tests were passed. Small-scale PVAC systems could also be built for the young children or teenagers.

5.3 Design Considerations for Future

Since we live in an age where technology is constantly changing and improving, design modifications could be made to greatly enhance the PVAC system. Areas to consider for further improvements include:
5.3.1 Improved Batteries

Currently the LiPo battery is the best when considering energy density. These batteries are made up of metal oxides (positive electrode) and a solid-state electrolyte (organic lithium solution). Since lithium is the third lightest material on the periodic table, these batteries are significantly lighter than lead-acid batteries. A new form of lithium battery is being researched. This “Lithium Air” battery operates by a reaction of air (cathode) circulating through a membrane of lithium ions (anode). It has a projected energy density of 5,000 watt-hours per kilogram. This is more than ten times the energy density of lithium ion batteries used today [6]. Unfortunately, this battery is still under development, and will not be available for another decade.

5.3.2 Active Noise Reduction

As the updated PVAC uses passive noise reduction methods to absorb sound, further considerations should include some way of implementing active noise cancellation. Active noise cancellation is the electronic form of eliminating noise. This method uses a device that senses noise via microphone. The properties of this noise may be statistically non-stationary. The electronics produce an anti-noise that is 180° out of phase with the original signal. It is transmitted by some form of electo-mechanical device canceling the original signal [7].
5.3.3 Vacuum Motor Selection

As manufacturing techniques continually improve, new motors that are more lightweight, efficient, and acoustically quieter will become available. This would greatly enhance the PVAC performance, as the motors are a big contributor to weight and noise. One thing to consider for the future vacuum motors is to make sure it can operate on both AC and DC systems (universal motors). AC systems are great for any recreational climbing, but DC is needed for any outdoor climbing situations where an AC source is not available.

5.3.4 Conformable Pads

Current pads seal to flat “sealable” surface, but the real challenge is to design a pad to conform to any surface. This would be the optimum choice for any situations where the surface is not flat or smooth. Theoretical ways of accomplishing this feat involve allowing the pad itself to bend and conform. To do this, the pad would have to be made of a highly compliant material that would not break under given loads. Another option is to partition the pads into three sections: flange, tapered region and top. These regions would be attached to each other via torsion spring or glued to a stiffer yet compliant material. The sectioned pieces could be made of composite material. The connecting regions and inner surface of the pad would have to be lined with a rubber-like material that could easily seal whenever the pad expanded or contracted.

5.3.5 Rechargeable System

For future systems, it would be nice to develop a PVAC where the external power source charges the batteries while onboard. This would be useful in charging the batteries and would be convenient to climb up the wall part way with the power cords, then unplug and climb with the batteries.

5.4 Additional Comments

To further reduce costs and avoid the hassle of ordering products, several pieces could be printed in-house using a 3D printer. For example, the plastic components used in the
hose connecting assembly could all be printed using the 3D printer. The interface could also be modified to be printed flat to reduce the trimming operation. The only necessary purchase would be the compression spring. Several pipe connectors could also be printed at low cost, and could be made with tighter tolerances to eliminate adhesives.

There are other ways to improve production and reduce weight. For example, a CNC knife cutter could be purchased to reduce time in rubber and EVA foam cutting operations. Current pads could also be made of composite material using unmachined pads as the tooling mandrel. This could further reduce weight, but would take longer to manufacture. Composite pads would require manual composite fiber layup and time would be needed to bake each composite pad.
References


Appendices
Appendix A

Additional FEA Results

A.1 Additional FEA of Aluminum Base

A first iteration of analysis was conducted by looking at the aluminum base without the handle attached. The 300-lb. vertical load was applied at the bolt hole region with the same vacuum loading of 3.5 psi and fixed regions around the flange area. A nonlinear static analysis was then conducted resulting in a max von Mises stress of approximately 13,000 psi and a safety factor of about 2.1. Displacement values were much higher with a maximum occurring just under 1/8 of an inch. Fig A.1 illustrates these values.

Fig. A.1: (a) Maximum displacement ≈ 0.12in, (b) Maximum von Mises ≈ 13,000psi

As illustrated in Fig A.2, high stress values were found near the pressure release hole, vacuum port hole, and regions were the aluminum base tapers down.
A.2 Additional FEA on Handle

Additional methods to obtain stress within the handle were investigated. This alternative method looks only at the handle. This handle has clamp/bolted boundary conditions at the bottom of the post with a 300-lb. vertical load applied at the handle grips. This particular case assumes that the bolt hole region is very rigid. Results from this loading case are shown in Fig A.3
A.3 U Bolt Analysis

A simple test was devised to determine if the U-bolt could withstand the given load condition. A load of 300-lbs. would be applied, representing a “worst case scenario”. Unfortunately, difficulties arose when trying to mate the U-bolt plates to the complex curvature around the base. A simpler test was conducted without the plates and lock nuts, and the model suggested that the U-bolt yielded. This was reassuring as much stress is redistributed due to the pressure plates and lock nuts. Actual testing was conducted over several cycles using up to 400-lb. loads with no yielding in the bolt hole region nor the U-bolt itself. Shown below are the FEA stresses and displacements for the simple test without pressure plates. (See Fig A.4)

Fig. A.4: (a) Displacement field of U-bolt, (b) von Mises stresses within the U-bolt

A.4 Additional FEA of Snowboard Baseplate

More realistic tests of actual loading were conducted upon the snowboard baseplate. The angle formed when the polyester straps were under full weight was approximately 60°. This is due to the carabiner that attaches at the center of the polyester straps. When FEA analysis was reiterated, stress values were much lower giving a safety factor of 2.1. Fig A.5 portrays the stresses and displacements within this model.
Fig. A.5: (a) Displacements within model, (b) Max Stress value of $\approx 13,000\text{psi}$

Another explored scenario was if half the weight was applied to the plate. This simulates a stationary condition, as half of climber’s body weight is transferred to each individual binding. This stress value would be useful for determining the number of cycles to failure. Values of these stresses and displacements can be found in Fig A.6

Fig. A.6: (a) Displacements within model, (b) Max Stress value of $\approx 6,600\text{psi}$
Appendix B

Additional Material Trade Studies

Other noteworthy material trade studies are attached in the following subsections. Some materials such as the *Stealth®* rubber were an obvious choice. Other simpler components implemented a generalized material selection chart shown in Fig B.1 (Blue = Best, Red = Worst)

![Image of material selection chart]

Fig. B.1: Basic material selection chart
B.1 Safety Interface Selection

Below in Fig B.2 is a trade study conducted for the safety interface devices. A temperature gauge was not implemented into the design as testing yielded safe temperature ranges at worst case scenarios.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Thermocouple</th>
<th>Vacuum Gauge</th>
<th>Voltage Monitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($)</td>
<td>10.80</td>
<td>12.77</td>
<td>.5</td>
</tr>
<tr>
<td>Weight (lbs each)</td>
<td>.06</td>
<td>.25</td>
<td>.1</td>
</tr>
<tr>
<td>Availability</td>
<td>Available</td>
<td>Available</td>
<td>Available</td>
</tr>
</tbody>
</table>

Fig. B.2: Safety interface trade study

B.2 Power Switch Selection

Fig B.3 illustrates a trade study for the power switch selection. The chosen method was to use a pulse width modulator or PWM to regulate power input.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Product 1</th>
<th>Product 2</th>
<th>Product 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce Power Consumption</td>
<td>Runs at 5% to 100%</td>
<td>Consumes Power</td>
<td>Reduces Power</td>
</tr>
<tr>
<td>Reduce Noise</td>
<td>X unknown</td>
<td>X unknown</td>
<td>X unknown</td>
</tr>
<tr>
<td>Less than 0.55 lbs.</td>
<td>0.29</td>
<td>0.51</td>
<td>0.10</td>
</tr>
<tr>
<td>Less than $25</td>
<td>20.38</td>
<td>14.82</td>
<td>2.13</td>
</tr>
<tr>
<td>Handles 20 A</td>
<td>40</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exceeds Requirements</th>
<th>Meets Requirements</th>
<th>Does Not Meet Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>Yellow</td>
<td>Red</td>
</tr>
</tbody>
</table>

Fig. B.3: Power switch trade study
Appendix C

Drawing Package

Attached below is an “As Built” Drawing Package. Further cost and weight information can be found in Section 3.3.3. Detailed cost and weight for individual subsystems can be found in Appendix G.

C.1 As Built Drawings
Suction Hose
Battery Harness
On Off Switches
Added Strain Relief
SECTION A-A
SCALE 1:2

ABS Post

Utah State University

NAME DATE
Rhet Astle

MATERIAL
ABS Plastic

TOLERANCES:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL 1/16
ANGULAR: MACH 2deg
THREE PLACE DECIMAL .005

SECTION A-A
SCALE 1:2

Rhet Astle

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Aluminum Pipe

UNLESS OTHERWISE SPECIFIED:

SCALE: 1:2
WEIGHT:

INTERPRET GEOMETRIC TOLERANCING PER:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: 1/6
ANGULAR: 1/4
BEND:
THREE PLACE DECIMAL

APPLICATION:

USED ON
FINISH

COMMENTS:

Q.A.
MFG APPR.
ENG APPR.
CHECKED
DRAWN

Rhet Astle

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Utah State University

Title: Aluminum Pipe

Size: 6061 T6

Rhet Astle

Drawing: PAD004

Scale: 1:2
Weight:

Sheet 1 of 1
Rubber Grips

DO NOT SCALE DRAWING

PAD005

SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
SCALE: 1:1 WEIGHT:

REVDWG. NO.

A

SIZE

A

DWG. NO.

PAD005

REV

1

1

1

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRAC TIONAL
ANGULAR: MACH:
BEND:
TWO PLACE DECIMAL:
THREE PLACE DECIMAL:

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

APPLICATION

COMMENTS:

Q.A.

MFG APPR.

ENG APPR.

CHECKED

DRAWN

TITLE:

Store Bought Rubber Grips

Tennis Grips

Rhet Astle

5 4 3 2 1
Fringe

UNLESS OTHERWISE SPECIFIED:
SCALE: 1:8
WEIGHT: ...

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: 1/16
ANGULAR: 2 deg
TWO PLACE DECIMAL: 0.06
THREE PLACE DECIMAL: 0.005

REVDWG. NO.
A

SIZE  DWG. NO.  REV
A  PAD006  

SCALE: 1:8  WEIGHT:  SHEET 1 OF 1

EVA Foam

Rhet Astle
2 3/16" 1 5/16" 1" 2 1/16" 1/16" For 1/2" Pipe Size

5/16"-18 Thread

1 3/8" 3/4" 2 3/16" 1/16"

For 1/2" Pipe Size

8896T68
U-Bolt with Mounting Plate

Type 304 Stainless Steel

http://www.mcmaster.com
(c) 2004 McMaster-Carr Supply Company

Unless otherwise specified, dimensions are in inches. Information in this drawing is provided for reference only.
Rubber Strip

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH.
BEND:
TWO PLACE DECIMAL
THREE PLACE DECIMAL

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL:

APPLICATION

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:

5 4 3 2 1

Rhet Astle

Store Bought

C4 Stealth Rubber

Rhet Astle

TITLE:
Rubber Strip

SIZE
DWG. NO.
REV

A
PAD010

SCALE: 1:8
WEIGHT:
SHEET 1 OF 1

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Rubber Strip

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

FRACTIONAL

THREE PLACE DECIMAL

INTERPRET GEOMETRIC TOLERANCING PER:

MACH BEND

TWO PLACE DECIMAL

DRAFTING:

NAME DATE

COMMENTS:

Q.A.

MFG APPR.

ENG APPR.

CHECKED

DRAWN

SIZE DWG. NO. REV

SCALE: 1:8 WEIGHT:

STORE BOUGHT

Mi6 Stealth Rubber

Rhet Astle

SolidWorks Student Edition.

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Thread length may vary from 1" to fully threaded in length.

5/32" Hex

0.437"

0.132"

1 1/4"

0.25"

1/4"-20 Thread

91255A544

Alloy Steel Button-Head
Socket Cap Screw
For 1/4"-20 Screw Size

7/16"

9/32"

94909A181
Self Threading
Nylon Hex Locknut
Washer thickness may vary from 0.05" to 0.08" in thickness.

For 1/4" Screw Size

Zinc-Plated Steel

USS Standard Washer

PART NUMBER

90108A413

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http://www.mcmaster.com
3/8" for #10-24 screw size

1/4" self threading nylon hex locknut
For #10 Screw Size

Washer thickness may vary from 0.03" to 0.17" in thickness.

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Zinc-Plated Steel
USS Standard Washer

PART NUMBER 90108A411
### Store Bought

**Title:** 5/16" x 1 1/4" Extension Spring

<table>
<thead>
<tr>
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<th>DATE</th>
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<td>Q.A.</td>
<td>COMMENTS:</td>
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<tr>
<td>Rhet Astle</td>
<td></td>
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</table>
Heat Shrink Tube 4"

Store Bought

Title:
Heat Shrink Tube 4"

Design:
Rhet Astle

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WD46 Button

Store Bought

SIZE  DWG. NO.  REV
A      PAD019  

SCALE: 2:1  WEIGHT:  SHEET 1 OF 1

Rhet Astle

ABS Plastic
K2 Snowboard Bindings

DO NOT SCALE DRAWING

FOOT001

SHEET 1 OF 1

SCALE: 1:1

WEIGHT:

REVDWG. NO. A

SIZE DWG. NO. FOOT001

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

Store Bought

K2 Snowboard Bindings

NAME DATE

COMMENTS:

Q.A.

MFG APPR.

ENG APPR.

CHECKED

DRAWN

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL:

Reinforced Nylon

APPLICATION

DO NOT SCALE DRAWING

SolidWorks Student Edition.

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Foot Support Bracket

Dimensions:
- 1.31
- R4.50
- 2.56
- R.13 TYP UNO  R4.01
- 1.22
- 2.66
- 4.10
- 1.63

Notes:
- 2 X 2.00
- 6 X 0.313 X 1.00 SLOT
- Foot Support Bracket

Scale: 1:2
Weight: 
Sheet 1 of 1

Unless otherwise specified:
- Dimensions are in inches
- Fractional: 1/6
- Angular: Mach. 0.05 deg
- Three place decimal: 0.005

Application:
- Used on Next Assy

Material:
- 5052-H32 Alum. 0.08 in

Interpret geometric tolerancing per:

Comments:

Utah State University

Q.A.
MFG APPR.
ENG APPR.
CHECKED
DRAWN

Drawn by: Rhett Astle

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1" Bar Slide

Store Bought

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1" Polyester Webbing

Store Bought

Polyester

Rhet Astle

Title:
1" Polyester Webbing

Sizes: A

Drawing: FOOT005

SHEET 1 OF 1

Scale: 1:1

Weight:

Rev:
Store Bought

Carabiner

Bravo Locker

Rhet Astle

5 4 3 2 1
Thread length may vary from 1" to fully threaded in length.
7/16" For 1/4"-20 Screw Size
9/32"
Washer thickness may vary from 0.05" to 0.08" in thickness.

For 1/4" Screw Size

Zinc-Plated Steel
USS Standard Washer

© 2009 McMaster-Carr Supply Company

McMASTER-CARR
PART NUMBER 90108A413
Zinc-Plated Steel
USS Standard Washer

http://www.mcmaster.com

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Information in this drawing is provided for reference only.
Plasti-Dip

Do Not Scale Drawing

FOOT008

Sheet 1 of 1

Scale: 1:1

Weight:

Store Bought

Plasti-Dip

Rubber Dip

Rhet Astle

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Pressure Gauge

Store Bought

SolidWorks Student Edition. For Academic Use Only.
PWM DC 9-60 V (20 A)

DO NOT SCALE DRAWING

SAFE006

SHEET 1 OF 1

REVDWG. NO. A

SIZE

DRAWN

CHECKED

ENG APPR.

MFG APPR.

Q.A.

COMMENTS:

Interpret geometric tolerancing per:

FINISH

APPLICATION

DO NOT SCALE DRAWING

Rhet Astle

Store Bought

PWM DC 9-60 V (20 A)

Rhet Astle

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Waterproof Voltage Display
8.5-90v DC 2 wire

DO NOT SCALE DRAWING

SAFE007
SHEET 1 OF 1
SCALE: 1:1
WEIGHT: 

REVDWG. NO.
A

NAME DATE

COMMENTS:

Q.A.
MFG APPR.
ENG APPR.
CHECKED
DRAWN

FINISH MATERIAL

INTERPRET GEOMETRIC TOLERANCING PER:

ASSY USED ON

APPLICATION DO NOT SCALE DRAWING

Store Bought

Waterproof Voltage Display
8.5-90v DC 2 wire

Rhet Astle

Title: Vacuum Hose

Store Bought

Rhet Astle

SAFE008

REV

SIZE

1 A

SolidWorks Student Edition. For Academic Use Only.
Vacuum Hose Gasket

Store Bought

Vacuum Hose Gasket

Rhet Astle

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Drawing Package

Climbers

4/16/2014
ITEM NO. PART # Manufacturer Location Price QTY.
1 P1 2 Wimmers $2 1
2 P2 1 Kleen Pro Vacuum Supplies www.kleenpro.com $92 2
3 P4 2
4 P5 1
5 P5 1
6 P6 1
7 4880K45 Wimmers $2 1
8 MV3SDC36V Kleen Pro Vacuum Supplies www.kleenpro.com $92 2
9 261242661418
10 WD50, WD45, WD47, WD46, WD86 Vacuum Hose Connector www.power-flite.com $22.36 2
11 4881K217 McMaster.com $10.92 2
12 1968 Central Vacuum www.centralvacuumstores.com $15 1
13 AQ1440IU48GCIND Synqor www.synqor.com $854 1
14 49371 Lowe's $2.06 2
15 Backpack Frame Amazon.com $36.99 1
16 1.5" Vacuum Pipe Whimmer $2.06 2
17 00337HO Cole Parmer www.coleparmer.com $53.32 2
18 RIVET Ipaco $.25 23
19 Latch Gate House Lowe's $3.37 3
20 10432400 www.soundproofcow.com $58.22 1
21 21362 Zippy $8
22 1x1 Wood Block 4
23 23473 Lowe's $4.33 2
25 21411 Lowe's $1.64 2
26 330543 Lowe's $3
27 73992
Notes:
1. Material: Polystyrene
2. Finish: Natural

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED

ANGLES = 0  30'
SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020
ALL SMALL FILLETS .020-.040
1. MATERIAL: POLYSTYRENE
2. FINISH: NATURAL

DIMENSIONS ARE IN INCHES

DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED

FRACTION = .001
.X = .1
.XX = .02
.XXX = .005
.XXXX = .0005

ANGLES = 0  30'

SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020
ALL SMALL FILLETS .020-.040

CLIMBERS
NOTES:
1. MATERIAL: POLYSTYRENE
2. FINISH: NATURAL

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING
PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED

FRACTION = .125
.X = .125
.XX = .02
.XXX = .005
.XXXXX = .0005

ANGLES = 0  30'
SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020
ALL SMALL FILLETS .020-.040

CLIMBERS
RIGHT HAND AND LEFT HANDED PWM COVERS

01-RIGHTHAND
02-LEFT HAND

REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE

DO NOT SCALE DRAWING SHT 1 OF 1

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NOTES:
1. MATERIAL: ABS
2. FINISH: NATURAL

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
FRACTION = 1/8
.X = .1
.XX = .02
.XXX = .005
.XXXXX = .0005
ANGLES = 0 30'

SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020
ALL SMALL FILLETS .020-.040

WEIGHT (LBS)

W.ELDER P5 A
12/2013

DETAILED BY
DESIGNED BY
ORIGINATION DATE

THIRD ANGLE PROJECTION

PWM COVER
125
NOTES:
1. MATERIAL: POLYSTYRENE
2. FINISH: NATURAL

WEIGHT (LBS): 0.377

DIMENSIONS ARE IN INCHES

DIMENSIONING AND TOLERANCING
PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED

FRACTION = 
0.125

X = 0

XX = 0.02

XXX = 0.005

XXXX = 0.0005

ANGLES = 0 30'

SURFACE ROUGHNESS
BREAK SHARP EDGES 0.010-.020
ALL SMALL FILLETS 0.020-.040
CLIMBERS 0

GROUP 8
SIZE: D
W.ELDER P6 A
4/14/2014

REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE
1. MATERIAL: ABS
2. FINISH: NATURAL
3. PURCHASE MCMASTER PART #4881K217 AND ALTER TO SPECIFICATIONS
For the following wiring diagram Please see the key presented in Table 1 as to specific wiring.
<table>
<thead>
<tr>
<th>#</th>
<th>Diagram</th>
<th>Description: For all cases Positive (red wire) and Negative (black wire)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="2 way male connector diagram" /></td>
<td>2 way male connector: Wire the positive always through the left and Negative through the right.</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2" alt="2 way female connector diagram" /></td>
<td>2 way female connector: Wired the same as 2 way male connector.</td>
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<tr>
<td>3</td>
<td><img src="image3" alt="4 way male connector diagram" /></td>
<td>4 way male connector: Top left = Negative Motor, Top Right = Positive Battery, Bottom Left = Negative Power, Bottom Right = Positive Power.</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4" alt="4 way female connector diagram" /></td>
<td>4 way female connector: Wired the same as 4 way male connector.</td>
</tr>
<tr>
<td>5</td>
<td><img src="image5" alt="Male terminal diagram" /></td>
<td>Male terminal: Always Soldered to the wire put in the Female connectors.</td>
</tr>
<tr>
<td>6</td>
<td><img src="image6" alt="Female terminal diagram" /></td>
<td>Female terminal: Always Soldered to the wire put in the Male Connectors.</td>
</tr>
<tr>
<td>7</td>
<td><img src="image7" alt="Pulse Width Modulator diagram" /></td>
<td>Pulse Width Modulator: from the left Positive to power, Negative to Power, Positive to Motor, Negative to Motor.</td>
</tr>
<tr>
<td>8</td>
<td><img src="image8" alt="Hoses diagram" /></td>
<td>Hoses: With the hoses oriented vertically connecting to the pad at the top end, the wire from the left side proceeding clockwise, Negative Power, Positive Power, Negative Motor, and then Positive Motor. This should be the same for both ends of the hose where the wires come out while oriented in the same position as that described above.</td>
</tr>
<tr>
<td>9</td>
<td><img src="image9" alt="Splice Connectors diagram" /></td>
<td>Splice Connectors: used at all junctions of two wires needing to be spliced together.</td>
</tr>
</tbody>
</table>

Table 1: Wiring Key for wiring diagram
Appendix D

Manual for Assembly

D.1 Assembly of Handle

*Tools you will need:*

- Flat end file
- 7/16" box end wrench
- 5/32" Allen wrench
- Two-part epoxy (resin and hardener)
- Silicone

The assembly of the handle occurs in two parts, the construction of the handle itself and then bolting the handle to pad. Steps illustrating these assemblies are as follows:

1. Cut a section of 1" nominal aluminum pipe to 7 inches long
2. Abrade the ends of each pipe section
3. Mix equal amounts of resin and hardener together
4. Apply epoxy mixture to each end of the pipe
5. Find (2) 3D printed post as shown in Fig D.1
6. Press fit each end of the pipe into post sections

7. Ensure the bottom of the new handle is level

8. Allow for a 24-hour cure of epoxy

9. Wrap handle with rubber grips

10. Find (4) of : 1/4” x 1 1/4” bolts, 1/4” washers, and 1/4” nylon lock nuts

11. Obtain 7/16” box end wrench and 5/32” Allen wrench

12. Line up the handle to the four pre-drilled handle holes

13. Put bolts through holes, attach each washer and hand tighten all four lock nuts

14. Tighten each bolt in a crisscross pattern to ensure each bolt is equally tight

15. Apply silicone to nut and washer region

D.2 Fringe Attachments

In order to successfully assemble the fringe components several steps have to be taken. The first steps to be addressed are how to bond the rubber strips to the pad and then move onto attaching the EVA foam.
**Attaching the Rubber**

*Tools you will need:*

- Utility knife
- Digital calipers
- Large square
- Flat end file
- Mineral oil
- Two-part epoxy (resin and hardener)
- (15) or more plastic clamps

The first step is to permanently attach the rubber shims and *Stealth*® rubber to the pads. Outlined below are steps to accomplish this task:

1. First, find a sharp and easy to use utility knife
2. Measure and mark several spots at roughly 0.58 in (one dot width)
3. Connect marks using large square to make a continuous line
4. Cut entire line and repeat to obtain two rubber shims
5. Repeat process for *Stealth*®, but cut four strips
6. Measure 23.5 inches on each rubber strip and cut
7. Next, roughen both surfaces of the strips with a file
8. Abrade the aluminum surface where rubber is to be attached using a file as shown in Fig D.2
9. Clean the rubber and aluminum surfaces using alcohol wipes or mineral oil

10. Finally, mix equal amounts of resin and hardener on disposable surface

11. Apply mixture to aluminum edge

12. Smooth out epoxy and wipe away any excess

13. Attach shims to epoxied surface

14. Cut any additional shim material

15. Clamp into place and let epoxy set for 15 minutes

16. Remove clamps off and make sure the surface has dried

17. Next, apply epoxy to shim surface

18. Attach first rubber strip and clamp into place

19. Adhere second strip and clamp into place

20. Trim rubber if excess is present

21. Let strips cure for 24-hours
Steps to attach EVA

Tools you will need:

- Large compass
- Permanent marker
- Double-sided tape
- Utility knife
- Mineral oil
- Two-part epoxy (resin and hardener)
- (15) or more plastic clamps

The following steps demonstrate how to permanently attach the EVA foam:

1. First, obtain a compass

2. Next, tape a marker to the compass and measure out 8.0 in from tip to tip

3. Then, draw out the first circle on the EVA foam sheet

4. Draw another circle at a radius of 7.125 in

Fig. D.3: (a) Compass with marker attached, (b) Drawing circles
5. Now, we are ready to cut. Find a long utility knife

6. Make an incision penetrating the entire thickness of the foam

7. Making sure the knife is all the way through, continue to cut out each of the circles

![Fig. D.4: (a) Knife penetrating thickness, (b) Cutting circles out](image)

8. Once both circles are cut out, clean surfaces to be adhered with alcohol wipes or mineral oil

9. Abrade aluminum surface where foam is to be attached (see Fig D.5)

![Fig. D.5: Abraded aluminum surface](image)

10. Mix equal amounts of resin and hardener and apply to aluminum rim

11. Smooth out epoxy and wipe away any excess
12. Once complete, attach EVA foam and clamp

13. Wait 24 hours for epoxy to completely set

14. Trim excess EVA foam to make flush against edge of pad

**D.3 Pressure Release Assembly**

*Tools you will need:*

- Permanent marker
- Two-part epoxy (resin and hardener)
- 3/8” box end wrench
- 1/8” Allen wrench
- Silicone
- Double-sided tape
- # 21 drill
- # 10 tap

1. First obtain a left and right 3D printed pressure release

2. Acquire a marker and trace the shape of each part as shown in Fig D.6
3. Trim out each outline and trim bolt hole region

4. Epoxy each of these outlines to the bottom of the pressure releases

5. Wait 24 hours for epoxy to cure

6. Outline pressure release shape in heat shrink tubing

7. Cut outline out and adhere to mouse pad material

8. Let heat shrink cure for 20 min or until hardened as shown in Fig D.7

9. Obtain (2): 1/4” x 3/4” hex head shoulder bolts, #10 nuts, and (6) #10 washers for each pad
10. For each side, add (2) washers to bottom pressure release for clearance purposes

11. Fasten until pressure releases slide with resistance

12. Apply silicone to nut and washer region

13. Attach spring to one end of the pressure release

14. Obtain (2) ABS spring buttons

15. Apply double-sided tape to bottom surface and position at bottom edge of pad

16. Attach spring to pressure release and ABS spring button as shown in Fig D.8

17. Next, drill hole for pressure release stop

18. Make a mark at 2.8 in down and 1.21 in to the right of pad center (Left Pad)

19. Obtain # 21 drill bit and drill hole

20. Tap hole with # 10 tap (Fig D.9)
21. Screw in post and add washer and nut to the bottom

22. Silicone the nut and washer area

**D.4 Pressure Release Sealing Material**

*Tools you will need:*

- Utility knife
- Two-part epoxy (resin and hardener)
- 3/8” box end wrench
- 1/8” Allen wrench

1. First, obtain one mouse pad

2. Cut mouse pad into 4 equal sections

3. Place mouse pad in location of pressure release and up against handle

4. Mark location of pressure release hole, bolt hole regions for stop and pressure release

5. Cut or puncture these location out using a utility knife or hole punch

6. Mix up resin and hardener

7. Line up mouse pad material at original location
8. Remove pad and coat region with epoxy

9. Line up mouse pad material with bolt hole regions and fasten into place

10. Let epoxy cure for 15 minutes (Complete cure in 24 hours)

D.5 Vacuum Hose Assembly

*Tools you will need:*

- Thread tape
- Utility knife
- Flat end file
- Two-part epoxy (resin and hardener)

1. Obtain vacuum hose (WD25) and cut in half (5 ft)

2. Use thread tape and wrap the severed end

3. Obtain an extra (WD24) hose cuff and thread on other end

4. Put vacuum hose gasket (WD23) in each end of the vacuum cuffs

D.6 Hose Connector Assembly

1. First, find spring and compress into hole on button base

2. Slide compressed spring and button base into suction coupler as shown in Fig D.10
3. Obtain button and line up slots to button base

4. Press firmly down until both components snap together

5. Next, make bottom of hose connection flush by milling, sawing, or use of lathe

6. Smooth flushed end with file

7. Apply alcohol or mineral oil to part and vacuum port hole

8. Mix equal amounts of resin and hardener together

9. Apply epoxy to circular end of hose connector
10. Smooth out epoxy and wipe away any excess

11. Allow 24 hours for epoxy to cure

D.7 Safety Ring Assembly

*Tools you will need:*

- Permanent marker
- Digital calipers
- Small square
- 5/16” drill
- (2) 5/8” box end wrenches

The safety ring assembly requires the following steps:

1. Draw one line that is parallel with bottom of handle post using flat ruler

2. Find center of this line (should measure 3.375 in to each post shown in Fig D.12)

3. Follow up that line with a perpendicular line

4. Extend this line past the tapered (drafted) region as shown in Fig D.13
5. Find the middle between the top and bottom of tapered region and mark

6. Forming a perpendicular line, measure 0.65 in on each side using calipers and mark

7. Obtain power drill with 5/16” drill

8. Drill pre-marked regions and deburr holes if needed

9. Repeat steps 1-8 for other pad

10. Insert U-bolt with nut and pressure plate on top surface as shown in Fig D.8 Pressure Gauge Hole

11. Attach an additional pressure plate with nuts to the bottom as shown in Fig

12. Tighten each side evenly and allow for space for carabiner attachments

**D.8 Pressure Gauge Hole**

*Tools you will need:*

- Digital calipers

- 1/2” drill

- Silicone

1. Obtain left pad and find digital calipers

2. Using calipers, measure 1.41 in from top left post and mark
3. Ensure this is straight by using square level and placing at top edge of left post

4. Drill marked spot to 1/2" diameter

5. Self-thread pressure release into a “upright” position as shown in Fig D.14

6. Repeat process for right side using top right ABS post as reference

7. Apply silicone to threaded areas

Fig. D.14: Complete pad with pressure gauge in “upright” position

D.9 Attachment of aluminum baseplate

Tools you will need:

- Permanent marker
- 1/4” drill
- 7/16” box end wrench
- 5/32” Allen wrench
1. First, open hatch to expose circular hole for nylon reinforced baseplate (Fig D.15)

2. Obtain aluminum baseplate and align with bottom of bindings

3. Line up nylon baseplate at zero degrees and make 4 markings at the center of baseplate slots

4. Repeat steps 1-3 for other side

5. Obtain 1/4” drill and machine at markings

6. Find (4) of: 1/4” x 1 1/4” bolts, 1/4” washers, and 1/4” nylon lock nuts

7. Obtain 7/16” box end wrench and 5/32” Allen wrench

8. Align baseplates to the 4 pre drilled holes

9. Put bolts through holes, attach each washer and hand tighten all four lock nuts

10. Fasten each bolt in a crisscross pattern to ensure each bolt is equally tight.

D.10 Polyester Webbing Sewing Instructions

*Tools you will need:*

- Utility knife
• Lighter (scorch ends)

In order to manufacture 1” polyester webbing sections the following materials are needed:

• 1” Polyester Webbing (300 ft preferred for 5 systems)

• 1” Cam buckle

• 1” Slide Lock

• Aluminum baseplates (Left and Right)

Steps to manufacture foot connection pieces are as follows:

1. Measure 5 1/2 ’ and cut (2) pieces of polyester webbing

2. Scorch ends of webbing to prevent fraying

3. Sew loop and one end of each piece for carabiner attachment

4. Loop remaining end through cam buckle and slide lock as shown below in Fig D.16

Fig. D.16: Looping through slide lock
5. Lastly, hem other end by 3/4" and sew

Next, pieces need to be sewn to aluminum baseplate. Steps are outlined below:

1. Measure 30" and cut (6) pieces of polyester webbing
2. Scorch ends of webbing to prevent fraying
3. Obtain left and right aluminum baseplate pieces
4. Sew each piece around slotted areas to obtain 3 loops on each baseplate
5. Finally, sew these 3 loops together to obtain carabiner loop as shown in Fig D.17

Fig. D.17: Sewn baseplate

**Tools you will need:**

- Permanent marker
- VacuForm box with mandrel
- (6) spring clips
- Vacuum motor
- 150 grit sandpaper
- Heat gun (if needed)
- Two-part epoxy (resin and hardener)
**D.11 Backpack Vacuforming**

In order to manufacture the backpack into its given shape, the following steps have to be followed:

1. First, partition 6’ x 3’ polystyrene into (3) 24 in x 24 in and (1) 12 in x 72 in sections (Fig D.18)

![Fig. D.18: Plastic partitioning](image)

2. Secure squared section wooden square via six evenly spaced spring clips (Seen in Fig D.19)
3. Place backpack tooling atop vacuform box

4. Preheat the oven to 330° F

5. Heat piece for 5-10 minutes until plastic sags around 4 inches

6. Engage suction to vacuform box

7. Drape plastic section over tooling mandrel and wait until plastic solidifies (about 20 s)

8. Defects can be handled either by heat gun or placing back in oven (Step 5)

9. This process creates (2) lids and (1) case (repeat for multiple boxes)

10. The final vacuformed part should look like Fig D.20
11. Next, cut vacuformed parts out using a band saw

12. Clean up rough edges using a disc sander

13. Smooth the edges further by using 150 grit sandpaper

D.12 Backpack Width Forming

*Tools you will need:*

- Plastic clamps
- Heat gun
- Madrel (width)
- 3/16” drill
- 3/16” aluminum rivets (50 pack)
- Rivet gun
- Two-part epoxy (resin and hardener)
• 150 grit sandpaper

1. Begin by obtaining 12 in x 72 in strip of polystyrene

2. Cut this strip in half to obtain a 6 in x 72 in pieced

3. Clamp one end of this strip to the width forming mandrel as shown in Fig D.21

4. Next, use heat gun to form strip around the wooden mandrel

5. Your last bend with excess strip material should look like Fig D.22
6. Place the formed width section (with excess material) inside vacuformed part

7. Measure and cut excess piece to form a snug fit

8. This 6” piece is now ready to rivet into place

9. Rivets are placed every 1.5” on the sides of the pack (width and vacuformed part)

10. First, drill a 3/16” pilot hole through both pieces for each rivet location

11. Rivet the vacuformed and width piece together

12. Lastly, epoxy loose edges of the 6” width piece together

D.13 Final Backpack Manufacturing Steps

Tools you will need:

- Two-part epoxy (resin and hardener)
- Phillips screwdriver
- 3/8” box end wrench
• Utility knife

• Double-sided tape

1. Drill holes for vacuum connectors, latches, and muffler

2. Epoxy hose connectors into place and allow cure time of 15 minutes

3. Next, bolt the latch pieces onto the lid and 6” width piece

4. Attach backpack and vacuum motors to the frame via cutting slits on the back section of the backpack

5. Obtain furring strip spacers and 7 1/2 in hose clamps

6. Place furring strips and the top and bottom of the frame for spacing purposes

7. Loop hose clamps through slits and motors

8. Hose clamps should be tightened so that motors do not move

9. Line the inside of the backpack with the acoustic foam pad

10. This is done by cutting to desired shape and attached via double-sided tape

11. Finally line muffler with acoustic insulation

12. Configure PVC piping as shown in Fig D.23
Fig. D.23: Internal piping setup

13. Attach muffler to PVC connector and through muffler hole
Appendix E
Operating Manual

E.1 Power Source Setup

Before setting up the power source make sure each pulse width modulator (PWM) dial, located on each suction pad, are turned to the off position (rotated completely counterclockwise). Additionally, ensure the analog switches (shown in Fig E.1) are switched to the off position to prevent arching at connectors.

![Fig. E.1: Switches enclosed to prevent accidental shutoff](image)

There are two options for power sources to the PVAC system. Two separate lids are used depending on which one is chosen.

- Batteries
- Converter

**Batteries**

The batteries are the mobile way of climbing structures. This method is typically used...
when A/C sources are unavailable. The batteries are configured so that four batteries are connected in parallel (two in series) for a total of eight batteries. Connecting in parallel allows for an increase in climbing time. To protect the batteries from harsh environments (rain, debris, etc...), the batteries are enclosed within the backpack as shown in Fig E.2. Furthermore, a battery harness (shown in Fig E.3) is used to allow for easy connecting. Lastly, tension relief was added to the wiring setup to prevent unwanted disconnecting during any point of the climb.

Fig. E.2: Internal backpack configuration

Fig. E.3: Battery harness with tension relief added
*Note* - To allow for a maximum in climbing time, make sure the batteries are fully charged to 4.2 volts per cell totaling 21 volts per battery.

Once batteries are connected and hoses are attached at pads and backpack ports(Figs E.4 E.5), the analog switches are ready to be turned to the on position.

![Fig. E.4: Pad connections](image)

![Fig. E.5: Backpack connections](image)
Converters

Converters are mostly used for any indoor climbing where A/C power sources are readily available. The converters are much simpler in setup. An additional lid with the converters bolted are are used. This requires the removal of the batteries and battery harness from the inside of the backpack. A converter harness is then put into place. Two converters are used to ensure additional safety just in case one motor or converter fails. The harness splits for each converter to connect to the converter output pins shown in Fig E.6. An additional power cable divider is used to provide power from the A/C source to the converter input pins (shown in Fig E.7). Lastly, the extension cord is then wrapped around the backpack frame for added tension relief (Fig E.8).

Fig. E.6: Converter harness at converter output
Once everything is setup for the converters, the analog switches can be flipped to the on position.

### E.2 Climbing Setup

In order to begin climbing, the PVAC has to be properly equipped. The top of the foot support straps and daisy chains loops have to be attached to the pads via carabiners. These carabiners are attached to the safety rings on the pads and tightened to the lock position. Additional carabiners are used to attach the bottom loops of the foot support straps to the boot bindings. The left and right sides of the daisy chains are then attached to the
center loop of the climbing harness by one carabiner as well. This setup is shown in Fig E.9.

Fig. E.9: Equipped PVAC ready to go

The climbers is now equipped to climb. The following steps are now needed before climbing begins:

- First the climber must put on the climbing harness making sure straps are tight
- The climber then steps into bindings, tightens ratchets, and locks feet into place by pull tab
- Next, the climber makes the figure 8 knot on the belay line
- The belay line is then looped through the climbers harness and tied through the figure 8 knot
- The backpack is then placed on the climbers back
- Adjustments are made on the backpack straps and foot support straps to fit the climber height and girth

After these steps are taken, the climber is ready to turn on the PWM dials to a range of 35-40 volts (as seen on the voltmeter). Make sure the LEDs are lighted up on the voltmeter. If not, there is some electrical issues are electrical connections/switches are not
made. Higher voltage is needed for harder to seal surfaces. Place the pads to the wall to check the vacuum pressure. If the vacuum pressure is above 55 in $H_2O$, the climber can safely ascend the wall. One pad can be moved to a higher position. This is done by pushing up with the thumb on the pressure release. Once the suction is disengaged from the wall, let go of the pressure release. The pressure release will spring back into place will the climbers positions the pad in the new position. The climber needs to move their foot at the same time as the pad. The climber then shifts their body weight to this newly adhered side. Move the other pad and foot using the same method. These steps are repeated until the climber is to the top, or ready to climb down. Climbing down the wall requires the same steps, but pads are lowered.

Additional notes for effective climbing:

- Use your legs. The foot supports are there for a reason.
- Move pad and foot at the same time
- Position pads at a height that you can handle. Too high or too low can greatly hinder climbing time.
- Release the pressure release when pad is not sucked to wall. If done while attached to wall, pressure release might stick or jam. This will not create a proper seal.
- Daisy chains can be used to rest if needed. Tighten straps so daisy chains take the weight.
- Be aware of your climb time when using the batteries. A maximum of 20 minutes is suggested before should descend down the wall
Appendix F

Maintenance Instructions

In order to upkeep the PVAC to operational standards, several components need to be maintained. These areas include:

- Fringe
- Pressure Release
- Polyester Webbing
- Hoses
- Batteries
- Vacuum Motors
- Electrical Connections

F.1 Fringe

The fringe materials (rubber and foam) need to be visually inspected before each climb to ensure no rips or tears. If present, resurface using brush grinder and replace using steps shown in Appendix D.2.

F.2 Pressure Release

As numerous dynamic cycles of the pressure release occur, several components can get wore out without proper care. Lithium grease needs to be applied to the bottom to the pressure release so smooth sliding occurs. Other components could also need replacing such as the extension spring, plastic heat shrink tubing, and possibly the pressure release itself. Steps to replace components can be found in Appendix D.3.
F.3 Polyester Webbing

Visual inspection of the polyester webbing should occur to make sure no fraying occurs. If so, discard webbing and either replace component or get it resown.

F.4 Hoses

Hoses should be checked every month for leaks. If leaks occur, fix using seal tape or depending on the severity, replace the component completely. Rubber seals also need to be checked as moisture build up can occur and render them useless.

F.5 Batteries

Batteries need to be monitored every charge cycle. This is required as failure can easily occur within a cell. Typically, these batteries can last up to 500 charge-discharge cycles. After this limit, LiPo batteries need to be discarded and replaced.

F.6 Vacuum Motors

Vacuum motors need to be checked regularly to ensure that the carbon brushes are functioning properly. If not, order additional brushes or replace motor as needed. Additionally, rotors need to be cleaned every 6 months to ensure no carbon debris from brushes clogs or ruins the motors.

F.7 Electrical Connections

The most typical failure occurs within the electrical side of things. Connectors can easily be pulled loose without proper tension relief, or soldering joints can fail over time. These failures typically require replacement or resoldering of the electrical connection. To the right of Fig F.1 shows a connector with proper tension relief.
Further improvements to reduce wire tension relief have come in the form of purchasing more flexible wire. This wire is used in the RC industry as is sheathed in silicone and has 660 strands of copper wire for ultimate flexibility. This wire has greatly reduced connection failures and has made soldering a dream.
Appendix G

Bill of Materials

Attached below in the proceeding appendix sections are estimated bill of materials for each subsystem.

G.1 Pad Subsystem Cost and Weight Estimations

Below in Fig G.1 is the cost and weight estimation of the pads. A 10% safety cushion was added to both cost and weight to account for possible missed items and unknown weight for smaller items.

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<th>Industry Part Number</th>
<th>Part Number</th>
<th>Qty</th>
<th>Item Description</th>
<th>Weight/System [lbs]</th>
<th>Cost/System [US$]</th>
<th>Supplier</th>
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<td>Alum. Pad 1S</td>
<td>1.68</td>
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<td>Alum. Tube 1&quot; Schedule 40 FTY</td>
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<td>APS Sporting Goods</td>
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<td>U-Bolts</td>
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<td>2</td>
<td>1/4&quot; x 1 1/4&quot; Cyl Screws</td>
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<td>1/4&quot; x 1/4&quot; Shoulder Screws</td>
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| Total                |             |     |                  | 8.37 lbs           | $549.21          | With Hard Rubber Used - 10% Cushion |
|                      |             |     |                  | 8.37 lbs           | $539.20          | With Soft Rubber Used - 10% Cushion |

Fig. G.1: Cost and weight estimation pads
G.2 Foot Support Subsystem Cost and Weight Estimations

Shown in Fig. G.2 is the cost and weight estimation for the foot support subsystem. An additional 10% safety cushion was added.

![Fig. G.2: Cost and weight estimation foot supports](image)

G.3 Safety Subsystem Cost and Weight Estimations

The cost and weight estimation for the safety subsystem can be found in Fig. G.3. An additional safety cushion of 10% was added.

![Fig. G.3: Cost and weight estimation safety](image)
G.4 Backpack Subsystem Cost and Weight Estimations

Fig G.4 illustrates the cost and weight estimations for the backpack subsystem. Two cases were considered, the backpack with batteries and the backpack with the converter.

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<th>Part Number</th>
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<td><a href="http://www.dekley.com">www.dekley.com</a></td>
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<tr>
<td>75099</td>
<td>BACK9352</td>
<td>18</td>
<td>16-14 MA Male Weather Pack Terminal</td>
<td>-</td>
<td>$8.36</td>
<td><a href="http://www.dekley.com">www.dekley.com</a></td>
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<tr>
<td>75010</td>
<td>BACK9362</td>
<td>7</td>
<td>18-14 Gauge Grey Cavity seal</td>
<td>-</td>
<td>$13.09</td>
<td><a href="http://www.dekley.com">www.dekley.com</a></td>
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<tr>
<td>WDC1200</td>
<td>BACK9372</td>
<td>2</td>
<td>Deans Silcone Wire 12 Gauge - Red</td>
<td>-</td>
<td>$64.00</td>
<td><a href="http://www.hobbybush.com">www.hobbybush.com</a></td>
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<tr>
<td>WDC1201</td>
<td>BACK9382</td>
<td>2</td>
<td>Deans Silicon Wire 12 Gauge - Black</td>
<td>-</td>
<td>$64.00</td>
<td><a href="http://www.hobbybush.com">www.hobbybush.com</a></td>
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<tr>
<td>AG2443426535</td>
<td>BACK9392</td>
<td>2</td>
<td>Converter</td>
<td>-</td>
<td>$2,214.00</td>
<td><a href="http://www">www</a>. impover.com</td>
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<tr>
<td>5AM7092336A</td>
<td>BACK9402</td>
<td>2</td>
<td>Converter Output Connector</td>
<td>-</td>
<td>$15.22</td>
<td><a href="http://www.pgooshop.com">www.pgooshop.com</a></td>
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<tr>
<td>3S12N4JL</td>
<td>BACK9412</td>
<td>16</td>
<td>Converter Output Contact</td>
<td>-</td>
<td>$27.68</td>
<td><a href="http://www.pgooshop.com">www.pgooshop.com</a></td>
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<tr>
<td>DW2212-17-S0C</td>
<td>BACK9422</td>
<td>2</td>
<td>Converter Input Connector</td>
<td>-</td>
<td>$17.58</td>
<td>Mouser Electronics</td>
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<tr>
<td>DFN21A-1416SC</td>
<td>BACK9432</td>
<td>6</td>
<td>Converter Input Output - Hirose Power to the Board</td>
<td>-</td>
<td>$18.93</td>
<td>Mouser Electronics</td>
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<tr>
<td>WOLX61-00020000</td>
<td>BACK9442</td>
<td>1</td>
<td>Converter Controler</td>
<td>-</td>
<td>$8.94</td>
<td><a href="http://www.dekley.com">www.dekley.com</a></td>
</tr>
<tr>
<td>WOLX61-00020000</td>
<td>BACK9452</td>
<td>1</td>
<td>Converter Controller Contact</td>
<td>-</td>
<td>$0.04</td>
<td><a href="http://www.dekley.com">www.dekley.com</a></td>
</tr>
<tr>
<td>IZ-1000-15-2S</td>
<td>BACK9462</td>
<td>2</td>
<td>4000 mah 18.5 x 35 Lithium Polymer Batteries</td>
<td>-</td>
<td>$308.80</td>
<td><a href="http://www.hobbybush.com">www.hobbybush.com</a></td>
</tr>
<tr>
<td>169666</td>
<td>BACK9472</td>
<td>1</td>
<td>Thunder-AOS-Charger Power</td>
<td>-</td>
<td>$48.95</td>
<td><a href="http://www.hobbybush.com">www.hobbybush.com</a></td>
</tr>
</tbody>
</table>

| Total Weight with Converter | 24 lbs | $1,051.96 |
| Weight with Batteries | 31.3 lbs | $1,200.82 |

Fig. G.4: Cost and weight estimation backpack
G.5 Tooling Cost Estimations

Lastly, the tooling cost estimation is shown in Fig G.5. A 10% safety cushion was added for any small tooling cost that were neglected or not considered. Also, another case was considered if no 3D printer cost was added since it has a large contribution to cost.

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Qty</th>
<th>Item Description</th>
<th>Cost/System ($)</th>
<th>Supplier</th>
</tr>
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<tr>
<td>TOOL001</td>
<td>1</td>
<td>Metal Spinning Die (PADS)</td>
<td>$685.00</td>
<td>Freedom Process Piping Inc.</td>
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<td>TOOL002</td>
<td>1</td>
<td>Creator 3D Printer</td>
<td>$1,148.00</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
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<tr>
<td>TOOL003</td>
<td>2</td>
<td>Octave 1.75 mm ABS Filament</td>
<td>$62.00</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
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<td>TOOL004</td>
<td>3</td>
<td>Octave Kapton Tape 6&quot; x 100&quot;</td>
<td>$45.00</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
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<tr>
<td>TOOL005</td>
<td>2</td>
<td>1/16&quot; 24&quot; x 46&quot; Acrylic Plastic Sheet</td>
<td>$122.23</td>
<td>Delmes Plastic</td>
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<tr>
<td>TOOL006</td>
<td>1</td>
<td>3/4&quot; PTFE Thread Seal Tape</td>
<td>$2.80</td>
<td>Home Depot</td>
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<td>TOOL007</td>
<td>2</td>
<td>22 Pc Spring Clamp Set</td>
<td>$17.94</td>
<td>Home Depot</td>
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<tr>
<td>TOOL008</td>
<td>5</td>
<td>Loctite Job Size Quick Set Epoxy 8 oz</td>
<td>$78.35</td>
<td>Home Depot</td>
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<tr>
<td>TOOL009</td>
<td>1</td>
<td>Scotch 1&quot; Double Sided Tape</td>
<td>$19.98</td>
<td>Lowe's</td>
</tr>
<tr>
<td>TOOL100</td>
<td>1</td>
<td>8.9 - Siliconia 9 oz</td>
<td>$5.98</td>
<td>Home Depot</td>
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<tr>
<td>TOOL101</td>
<td>1</td>
<td>12 in Combo Square</td>
<td>$6.99</td>
<td>Harbor Freight</td>
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<tr>
<td>TOOL102</td>
<td>1</td>
<td>Fold Lock Utility Knife</td>
<td>$5.99</td>
<td>Harbor Freight</td>
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<tr>
<td>TOOL103</td>
<td>1</td>
<td>Hex Key T Handle 10 pc</td>
<td>$6.99</td>
<td>Harbor Freight</td>
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<tr>
<td>TOOL104</td>
<td>1</td>
<td>Bernzomatic 1/8 lb Lead Free Solder</td>
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<td>Lowe's</td>
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<tr>
<td>TOOL105</td>
<td>1</td>
<td>Acrylic Adhesive 45ml Cartridge</td>
<td>$12.77</td>
<td><a href="http://www.ellsworth.com">www.ellsworth.com</a></td>
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<tr>
<td>TOOL106</td>
<td>1</td>
<td>Mixing Nozzles</td>
<td>$13.56</td>
<td><a href="http://www.ellsworth.com">www.ellsworth.com</a></td>
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<td>1</td>
<td>Dremel Cutting Tool</td>
<td>$6.18</td>
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<td>TOOL108</td>
<td>3</td>
<td>Binder Clip 8 Pack</td>
<td>$13.47</td>
<td>Staples</td>
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<tr>
<td>TOOL109</td>
<td>1</td>
<td>Metallic Sharpie Pen</td>
<td>$5.00</td>
<td>Staples</td>
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<td>TOOL110</td>
<td>1</td>
<td>Elmer's 16 oz Wood Glue</td>
<td>$4.98</td>
<td>Lowe's</td>
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<tr>
<td>TOOL111</td>
<td>1</td>
<td>1/2&quot;x8'x8'x8' 2x4 Pine Lumber</td>
<td>$3.98</td>
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<tr>
<td>TOOL112</td>
<td>1</td>
<td>0.8 in x 10 ft Brown weather/dripping</td>
<td>$7.86</td>
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<td>TOOL113</td>
<td>1</td>
<td>2x4x6 in Kiln Dried Whitewood Stud</td>
<td>$1.98</td>
<td>Lowe's</td>
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<tr>
<td>TOOL114</td>
<td>1</td>
<td>Chamfer 45 1/2 Shank</td>
<td>$10.00</td>
<td>Industrial Tool And Supply</td>
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<tr>
<td>TOOL115</td>
<td>2</td>
<td>Premium Furring Strip 1x2x8</td>
<td>$1.94</td>
<td>Lowe's</td>
</tr>
<tr>
<td>TOOL116</td>
<td>1</td>
<td>2x4x14 AWG Stranded Red AND BLACK</td>
<td>$9.92</td>
<td>Lowe's</td>
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<tr>
<td>TOOL117</td>
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<td>2x6x10 Kiln Dried Douglas Fir Lumber</td>
<td>$6.52</td>
<td>Lowe's</td>
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<tr>
<td>TOOL118</td>
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<td>3M 1.08-in x 165-ft White Duct Tape</td>
<td>$1.75</td>
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<tr>
<td>TOOL119</td>
<td>1</td>
<td>Weather Pack Removal Tool, Delphi</td>
<td>$2.77</td>
<td><a href="http://www.delphi.com">www.delphi.com</a></td>
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<td>Total</td>
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<td>$2,577.20</td>
<td>10% Safety Cushion</td>
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<td></td>
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<td>$1,196.70</td>
<td>Neglecting 3D Printer</td>
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Fig. G.5: Cost estimation tooling