Shape Memory Polymer Composite Deployment in Near Space Environments: 

* A sub project of the WSU High Altitude Balloon Program *

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1. Executive Summary

The establishment of the Wright State University (WSU) high altitude balloon program creates an opportunity to conduct experiments in near space environments. Recently developed materials such as shape memory polymer composites are ideal for space applications due to their high specific stiffness (elastic modulus divided by density) and ability to be stowed into a small size for launch in conventional space vehicles, then deployed to full operational size and form once in space. Such characteristics allow for space based structures to become larger and lighter than structures currently used in space. There are various issues associated with deploying shape memory polymer composites in space, such as deployment characteristics in zero gravity, activation of the shape memory properties, and achieving the power required for activation and deployment of the shape memory polymer composite. However, testing materials in space based environments is often impractical due to the complexity and cost involved. This creates an opportunity to conduct testing of a shape memory polymer composite, provided by ILC Dover, in near space environments using a high altitude balloon platform. By the end of this project, the design team plans to have accomplished the deployment of a shape memory polymer composite during the flight of a high altitude balloon platform.

2. Introduction

2.1 Purpose

The goal of this project is the deployment of a shape memory polymer composite in a near space environment using a high altitude balloon and associated modules as the deployment platform. Such a project is necessary to conduct research into techniques for deploying smart materials such as shape memory polymers in space and other extreme environments. Very little information concerning the performance of shape memory polymer composites in space is known. The purpose of this project will be to learn more about shape memory polymer composites and their viability for space based environments by deploying a shape memory polymer (SMP) composite boom at approximately 100,000 feet in altitude on a high altitude balloon platform.

2.2 Background and Significance

The establishment of the WSU High Altitude Balloon Program opens the door for experiments to be conducted at 100,000 feet in altitude in a near space environment. ILC Dover has provided WSU with a shape memory polymer composite tube. Smart materials such as shape
memory polymer based composites have properties that make them ideal for application to space based systems. Shape memory polymers are unique materials systems that demonstrate the ability be deformed at elevated temperatures and cooled into a variety of different shapes; upon re-heating, the SMP will return to its original “memorized” shape. The temperature above which the SMP gains the ability to be deformed and/or return to its original shape is known as the glass transition temperature (Tg). SMPs are in a rigid plastic state below their Tg and are in a flexible, elastomer state above their Tg. Figure 1 below is plot demonstrating a typical Elastic (storage) modulus versus temperature curve for a shape memory polymer or shape memory polymer composite.

![Figure 1: Typical elastic modulus versus temperature curve for shape memory polymers and their fiber reinforced composites (source: http://www.crgrp.net/tutorials/smp2.htm [1])](image)

Shape memory polymers can be easily integrated into a polymer matrix, fiber reinforced composite, thus creating a shape memory polymer composite. SMP composites are similar to other polymer matrix composites in that they too have relatively high specific stiffness (elastic modulus divided by specific gravity). SMP composites can be applied to a wide variety of applications. One field of potential application is in space based structures, specifically in
imaging and communications satellites as well as space based propulsion systems. Current and future demands for satellites require larger aperture systems into the 10m to 300m diameter range, resulting in a system that is too big and too heavy to launch when using current state of the art technology that involves mechanized deployment. An SMP composite satellite could be heated and formed to fit into a small storage device (AKA “Stowing”) capable of fitting into a space launch vehicle, launched into space to the desired orbit, unpackaged, and then heated to deploy the satellite to its memorized operational shape; demonstrating the potential for SMP composites to solve such problems that modern mechanized systems exhibit.

However further space based research and development needs to be conducted in order to assess SMP composite performance as a space based material and at a systems level before potential commercial and government customers will be moved to integrate SMP composites into their systems. True space based testing is often requires large amounts of time and can also be prohibitively expensive. This creates a need for an inexpensive and relatively easy to work with platform for simulated space based testing, such as high altitude balloons. High Altitude Balloons demonstrate the ability to allow for this type of testing. High altitude balloons can go up to altitudes of 100,000ft – 150,000ft, which is termed as a near space environment. A near space environment has 99% vacuum, 98% to 99% gravity, and ranges in temperature from -60°C to -20°C. Figure 2 below shows variation elevations above ground and common names given to various altitudes.
High altitude balloons have a fairly standard configuration involving a latex balloon, parachute, rigging and connecting lines, command module, and payload module. Figure 3 below is a schematic of a typical high altitude balloon stack.
The command module is the capsule that contains the tracking and communications equipment necessary for tracking and recovering the balloon system. It can also contain cameras for recording images during flight and a micro processor for running the various systems on board the high altitude balloon system.

The payload capsule, as the name implies, carries any additional payload such as an experiment. In the case of this project, it will be carrying the equipment and materials related to the SMP composite deployment experiment.
The shape memory polymer composite needs to be packed while on earth, launched up to 100,000 feet, heated and deployed, and then characterized to assess the degree to which the shape memory polymer composite returned to its memorized shape.

2.3 Objectives

As stated previously, the main objective of this research is to deploy a shape memory polymer composite on a high altitude balloon platform during flight of the balloon. Throughout the project, some sub-goals will be achieved. This includes gaining more information about shape memory polymer composites, research into various power sources available for use in near space environments, and investigation of various heating technologies available for use in deploying shape memory polymer composites in operational environments.

3. Design Criteria

The design criteria associated with the SMP composite involves various temperature and deployment requirements. Every point of the SMP composite needs to be heated to a minimum temperature of 158°F (70°C). In order achieve optimum deployment of the SMP composite, the composite should be heated to 190°F (88°C) in an ideal situation. The reason for this is that the minimum heating temperature is the material’s glass transition temperature and maximum energy is achieved in the shape memory polymer molecules only after the shape memory polymer is heated to temperatures above the glass transition temperature. Heating the composite to higher temperatures requires more energy and has the potential of damaging the composite material. In fact the upper temperature limit of the shape memory polymer composite is 250°F (121°C). In order to assist with the deployment of the composite, the composite needs to be pressurized to 6psi during deployment. The amount of energy used for deployment needs to be at a minimum due to the weight and cost associated with large amounts of required energy.
The payload box in which the deployment of the composite will occur also has various design criteria associated with it. First of all, it needs to be able to withstand a temperature close to the maximum temperature of the SMP composite material, 250°F (121°C). The box must be able to withstand the temperature of the outside environment as well. These temperatures can be as low as -85°F (-60°C). The final box design must also have minimal heat losses to the environment. The box structure must be large enough to incorporate the composite material (with an operational work space requirement of at least 24”Long x 7”wide x 7”high), the power source to be used in heating the SMP composite, and the cameras to be used in the characterization of the SMP composite’s shape before and after deployment. The box must also be able to withstand the impact with the ground upon return to earth.

This launch and deployment of the SMP composite must also simulate a space based launch and deployment as closely as possible. This means that the composite must be exposed to the environment during heating and deployment. This also requires that the experiment must be able to begin and end autonomously. This means that the heating, pressurizing, and characterizing would not begin until a specified altitude. This altitude has not been set at a specific requirement.

The entire system must also satisfy FAA regulations. The regulation the apples to the system is FAR 101. The primary constraint limiting the design of the system is the weight limit of 12 pounds total payload weight (weight of all capsules combined), and a limit of 6 pounds per box. This means that the payload box needs to stay at 6 pounds or less when fully loaded.

4. Overall Project Review

The overall project approach was to break the project down into different areas, thus creating sub-projects: heating, pressurization, payload box, characterization, stowing, and launch. Each sub-project would be completed with the overall design criteria in mind. Then once
each sub-project was complete, all of the areas would be put together in a step-wise fashion. This is specifically the focus for areas that may have an effect on each other. Such as heating and pressurization, or ground based deployment and in-flight deployment. Using this step wise addition approach helps with trouble shooting and/or investigation into the effects of systems upon each other.

The sub-projects were assigned a lead person, with individual tasks broken down for each sub-project. A lead and a secondary person was assigned to every planned task, outlined in Table 1 below.
Table 1: Individual Assignments

<table>
<thead>
<tr>
<th>Task</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
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<td>Heating</td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Qualitative composite material testing</td>
<td>Brandon</td>
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<tr>
<td>Power Requirement Calculations</td>
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<td>Investigation of potential heating methods</td>
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<td>Survey of potential heaters - candidate heater list creation</td>
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<tr>
<td>Survey and selection of power methods</td>
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<tr>
<td>Drawings of composite and composite with heaters</td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Simulink model of composite heating and deployment</td>
<td>Jennifer</td>
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<tr>
<td>Device for stowing composite</td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Set up lab view for experimentation</td>
<td>Brandon</td>
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<tr>
<td>Set up electronics for experimentation</td>
<td>Chris</td>
<td>Jennifer</td>
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<tr>
<td>Set up composite for experimentation</td>
<td>Brandon</td>
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<tr>
<td>Data reduction from experimentation</td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Optimization of Heater location</td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Integration of selected power source</td>
<td>Chris</td>
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<td>Circuitry to ensure safe, constant heating to composite</td>
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<td>Jennifer</td>
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<td>Triggering system to start heating</td>
<td>Chris</td>
<td>Brandon</td>
</tr>
<tr>
<td>Triggering system to terminate heating</td>
<td>Chris</td>
<td>Brandon</td>
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<tr>
<td>Experimental and inflight data logging system for temperature</td>
<td>Chris</td>
<td>Brandon</td>
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<tr>
<td>of composite over time at multiple locations</td>
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<tr>
<td><strong>Payload Box</strong></td>
<td>Jennifer</td>
<td>Brandon</td>
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<tr>
<td>Payload box design</td>
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<td>Brandon</td>
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<tr>
<td>Payload box drawings</td>
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<td>Brandon</td>
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<tr>
<td>Payload Box Construction</td>
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<td>Brandon</td>
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<tr>
<td>Valve for pressurization</td>
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<tr>
<td>Adhesive for attaching and sealing payload box walls</td>
<td>Jennifer</td>
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<tr>
<td>Rigging for attaching Payload box to HAB stack</td>
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<td>Triggering of pressurization</td>
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<tr>
<td>Placement of Components in Payload Box</td>
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<td><strong>Pressurization</strong></td>
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<td>Development of concepts</td>
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<td>Downselection of pressurization concept</td>
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<td>Brandon</td>
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<tr>
<td>Fabrication of End caps</td>
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<td>Brandon</td>
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<tr>
<td>Adhesive for attaching End cap to composite</td>
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<td>Brandon</td>
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<tr>
<td>Pressurization Concept design</td>
<td>Jennifer</td>
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<td>Pressurization Modeling</td>
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<tr>
<td>Pressurization Experimentation</td>
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<td>Pressurization Concept Implementation</td>
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<td><strong>Characterization</strong></td>
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<td>Jennifer</td>
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<tr>
<td>Camera Selection</td>
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<td>Chris</td>
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<tr>
<td>Characterization Strategy</td>
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<td>Jennifer</td>
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<tr>
<td>Camera Placement</td>
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<td>Jennifer</td>
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<tr>
<td>Select and implement characterization software</td>
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<td>Jennifer</td>
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<tr>
<td>Selection and implementation of targets</td>
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<td>Jennifer</td>
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<tr>
<td>Characterization experimentation</td>
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<td>Jennifer</td>
</tr>
<tr>
<td>Characterization trigger to start taking of pictures</td>
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<td>Brandon</td>
</tr>
<tr>
<td><strong>Stowing</strong></td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Device design and construction</td>
<td>Brandon</td>
<td>Jennifer</td>
</tr>
<tr>
<td>Experimentation</td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td><strong>Electronics and in-flight data logging</strong></td>
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<tr>
<td><strong>System Level Testing</strong></td>
<td>Brandon</td>
<td>Jennifer</td>
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<tr>
<td>Assembly of all components</td>
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<td>Brandon</td>
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<tr>
<td>System testing</td>
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<tr>
<td>Data Collection and Reduction</td>
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<td>Jennifer</td>
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<tr>
<td>System weight assessment</td>
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<td>Jennifer</td>
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<tr>
<td>Launch of experiment on HAB balloon</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Control initiation and termination of experiment</td>
<td>Chris</td>
<td>Brandon</td>
</tr>
<tr>
<td>Data Reduction from in-Flight Experiment</td>
<td>Brandon</td>
<td>Jennifer</td>
</tr>
</tbody>
</table>
4.1 Heating

4.1.1 Initial planned approach

The initial approach planned for the development of the heating system began with calculating the worst case power requirements and determining the type of heating method and modes. Then the next step would be to create a model for the heating of the composite, experimentally validate and tune the model, and use the model to determine the best type of heaters and optimum heating design. This optimized design would then be assembled and then experimentation on this heating design would be conducted. Using this design had the intentions of saving time and cost to the project.

4.1.2 Discussion

The actual approach taken for the heating system design resembles the beginning of the planned approach where the worst case power requirements were calculated first. The worst case power requirement indicates that the power that would be required to heat the composite was calculated using conservative scenarios and values. Fundamental heat transfer equations for conduction, radiation, and convection were used in the power calculations. The assumptions made for the worst case power requirement are listed below.

The first assumption is that the composite is fully deployed when heating. This had an affect on the calculations for radiation and convection. Assuming that the composite is in its original memorized shape while heating makes the surface area for radiative loss and convective loss significantly larger than what would actually be acted upon while the composite is initially stowed before deployment.

The next assumption was that the temperature that the composite was being heated to was 90°C. The minimum temperature for deployment is 70°C, so assuming that the composite would
be heated to 90°C in all calculations provided a conservative measure for the amount of power needed to heat the composite.

Another assumption was that the end caps that were attached to the composite would be heated to 90°C in order for the composite to have enough energy to deploy. The reality was that the end caps would not need to be at a uniform 90°C for the composite to deploy. The actual scenario would be that the end caps would have a thermal gradient in them. Assuming that the entire end cap was at 90°C resulted in another conservative calculation for the power required to heat the composite listed as conductive losses in subsequent power calculations.

A final major assumption was that the composite’s initial temperature was that of ambient at 90,000ft which is approximately -20°C. The final design for the entire system and how the composite would mounted in the box would affect the temperature of the composite at the onset of heating. One possible scenario of how this would happen would be that the composite is mounted to the payload box by one of the end caps. The end cap inside of the box would then be close to the actual temperature inside of the box. The temperature inside of the box would be higher than ambient since the box is insulated. However using the ambient temperature for this altitude provided a safe worst case assumption. Figure 4 below indicates the ambient temperature as a function of altitude.
The equations (pulled from *Heat and Mass Transfer, Cengel [4]*) and specific calculations for the power requirements can be found in Appendix III. A summary of the power requirements is below Table 2.

**Table 2: Power requirements for heating composite**

<table>
<thead>
<tr>
<th>Power term</th>
<th>20°C, 1atm</th>
<th>20°C, Vacuum</th>
<th>90,000-100,000ft, -20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to heat composite (W)</td>
<td>9.41</td>
<td>9.41</td>
<td>14.8</td>
</tr>
<tr>
<td>Conductive losses (W)</td>
<td>32.34</td>
<td>32.34</td>
<td>50.86</td>
</tr>
<tr>
<td>Radiative Losses (W)</td>
<td>96.8</td>
<td>96.8</td>
<td>78.75</td>
</tr>
<tr>
<td>Convective Losses (W)</td>
<td>78.71</td>
<td>0</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Total Power Required (W)</strong></td>
<td><strong>217.3</strong></td>
<td><strong>138.6</strong></td>
<td><strong>147.5</strong></td>
</tr>
</tbody>
</table>

In selecting the heating method, the requirements for the project were and the nature of the smp composite was taken into consideration. The requirements for the project state the composite boom be deployed while exposed to the environment. This ruled out any options that may have allowed for enclosing the smp composite in a chamber that would have allowed for purely radiative heating. The decision at this point was that conductive heaters would be used. In
keeping in mind that the composite would be folding during and unfolding during deployment, it was established that flexible, conductive heaters needed to be used. This led to the decision of using flexible resistive heaters from Minco [5]. The reason for using Minco was upon a recommendation from a colleague that had previous favorable experience with Minco.

Upon determining how much power is required for heating the composite the available power sources were considered. Among the various power sources available such as solar cells and various forms of batteries, the power source that had the best balance of being the most powerful, lightweight, and cost effective option were lithium ion battery packs used in cordless power tools. In particular, the two lithium ion batteries that were selected for further investigation were an 18V, 3.0 Amp-hour LXT Makita lithium ion battery and a 28V, 3.0 Amp-hour Milwaukee lithium ion battery. These two batteries are shown below. Further decisions on these batteries will be discussed later in this section when more about experimentation is discussed.

The next step was to determine the best type of flexible heaters to use that would provide a heating system with optimal balance of cost, weight, power distribution, and efficiency. The initial plan was construct a model of the heating of the composite using simulink, and then steps
would be taken to experimentally validate and tune the model. However, as further discussion will reveal, modeling of the heating of the tube proved to be rather challenging and was taking too long to make any significant progress.

The ideal vision for what the heating model would be able to do was to replicate the experiment with in 10% error. This means that a heat flux could be applied over a certain area in the model and affects similar to what were found with experimentation could be found using the model. This would have allowed for a simulated model of the heating system and would save on costs of purchasing numerous types of heaters. The model that was able to be created before this effort was suspended due to time constraints can be found below. It focuses on even heating of the composite and models the temperature of the composite over time, thus creating more of a transient heat transfer model, when a quasi-steady-state heat transfer model of the temperature versus location was desired.

![Figure 7: Original Simulink Model of Temperature versus Time](image-url)
Instead of using the model to design the heating system, an experimental approach was taken. Due to the nature of polymer composites, the thermal gradients in these materials can be rather high due to the relatively low thermal conductivity. This essentially means that the more surface area that could be covered with heaters is desirable in additional to the optimum balance of factors listed previously.

The first step in the modified approach was to create a list of candidate flexible kapton resistive heaters. The compilation of this list looked at primarily rectangular heaters since they provide more versatility in being able to wrap the heater around the composite like a band or mount it along the length of the composite. The candidate heater list was created simply by selecting the highest power output heaters available. Rudimentary calculations were then performed on if the total number of heaters required to meet the maximum power of 217W would fit on the composite. After that the total cost of each heater was listed, along with the total cost of the heating system that would be associated with each heater. The heaters were first filtered by the length of the heater, with a limit set at a minimum length of 10 inches. This would allow for the heater to be wrapped around the composite or run along the length with maximum surface area coverage. The heaters were then filtered by the total number of heaters that would be required to reach the 217W goal. The limit set on the number of heaters at that period in time was 4 heaters. The final list of heaters selected for experimentation is shown below.

<table>
<thead>
<tr>
<th>Part #</th>
<th>Op Temp (°C)</th>
<th>Voltage (V)</th>
<th>Heater area (in²)</th>
<th>Heater Wattage (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK5288</td>
<td>90</td>
<td>18</td>
<td>5.54</td>
<td>72</td>
</tr>
<tr>
<td>HK5397</td>
<td>90</td>
<td>18</td>
<td>14.84</td>
<td>55.86</td>
</tr>
<tr>
<td>HK5168</td>
<td>90</td>
<td>18</td>
<td>13.51</td>
<td>53.11</td>
</tr>
<tr>
<td>HK5431</td>
<td>90</td>
<td>18</td>
<td>19.02</td>
<td>49.85</td>
</tr>
<tr>
<td>HK5390</td>
<td>90</td>
<td>18</td>
<td>8.34</td>
<td>92.56</td>
</tr>
</tbody>
</table>
Experimentation with the heaters was designed to investigate one heater at a time, mounted along the outside of the length of the composite. A thermocouple measurement device that could read 8 thermocouple channels at time and plot them to a virtual strip chart on provided software was obtained for the purposes of experimentation. The software that came with the device had that capability to save the data in the form of an excel spread sheet. This data measurement device has the ability to read data from multiple forms of temperature sensors, but for the purposes of this experimentation, type t thermocouples were found to be sufficient. This device is pictured below, and was purchased from Adept Scientific [6] at a discounted rate.

![Temperature measurement device](www.adeptscientific.co.uk [6])

Figure 8: Temperature measurement device

The thermocouples were placed at the midpoint of the length of the heater, at each end of the heater, and in the location determined to be the cold spot. The thermocouples at the mid length point of the heater start 1 inch away from the heater at 2 inch spacing after that, running until the thermocouples are approximately directly across from where the heater is located. The thermocouples at the ends of the heater were approximately 1 inch from the heater, and the cold spot thermocouple was placed directly opposite the heater as far down on the composite as possible. The schematic below gives a 1D representation of this above description.
Initial experimentation was conducted in Standard Temperature and Pressure (STP) by powering the heater with 18VDC from a dc power supply and measuring the resulting temperature distribution. The results of these experiments show that the convection acting on the composite skews the temperature distribution in the composite such that the upper portion of the composite is warmer than the lower portion of the composite. A plot representative of this effect is shown below. In order to ensure that the temperature of the composite was being measured, the thermocouples were insulated from the outside air by taping pieces of insulation over the thermocouples.
Another particularly interesting observation from the heating experiments during this phase is that the locations on the composite across from the heater is just as warm as the thermocouple right next to the heater (ch2 and ch3 are similar temperature to ch0 and ch1). This indicates that radiation is also occurring with these heaters.

In trying to establish a better method for experimenting with single heaters, a vacuum chamber was located and loaned for use to the high altitude balloon team by the Wright State Physics Department. A picture of this vacuum chamber is below. One challenge faced the team when this vacuum chamber was acquired, and that was running thermocouple wires and power leads into and out of the vacuum chamber while still maintaining a vacuum. The solution to this problem was found in a bolt with the middle bored out. The leads and wires would be run through this bored out bolt and then rtv silicone was used to fill in the area in between and around the wires. A picture of this design is shown below as well.
Using the same thermocouple locations as previously, the temperature distribution of using the same heater as in trial 6 was established for a vacuum chamber (no convection). This chart can be seen below.
As can be observed, the location right next to the heater became the warmest, but there was still significant radiation occurring across the composite.

Through out the course of the single heater experiments, a few lessons were learned. First of all, as previously mentioned, there is both conduction and radiation occurring as heat transfer modes. Secondly, more powerful heaters are not necessarily better because they typically come in smaller areas, which equates to significantly higher heat fluxes than the larger area heaters. This damages the polymer matrix with in the composite. Thirdly, locations at the end of the heaters are not heated as well as locations along the length of the heaters.

These lessons led the team to making a decision on the heating system design. The heating design needs to promote both radiation and conduction, and the heaters need not be too small so as to create higher thermal gradients, and heaters need to run the length of the composite to ensure as much area as possible is acted upon by the heaters.

### 4.1.3 Final Heating System Design
The final system design uses three strips of two heaters per strip. In each heater strip two heaters, 10 inches long each, are placed such that their combined length is 20 inches. The three heater strips run the length of the inside of the composite angled 120° from each other, so as to optimize both radiation and conduction. The reason for placing the heaters on the inside of the composite is to make it such that nearly 100% of the energy from the heaters is supplied to the composite. The type of heater being used is Minco HK5167, and at 18V they supply 35W per heater. So a system of 6 total heaters puts out 210W in an ideal power delivery design. The two heaters for each strip are connected in parallel and then run through the end cap, developed for pressurizing, to a controller. There is one controller per heater strip, totaling to three heaters, and one thermistor per controller. The controllers used with this type of heater are known as a ct325 controller, again from Minco. The controllers, heaters, and a thermistor are shown below in Figure 14. A view of the inside if the composite showing the heater strips follows as well.

![Heaters, controllers, and a thermistor used heating system design](image)
The heater leads that pass through the end cap were fixed into place and sealed by using a 1cc syringe to inject Tiga MD 48 epoxy resin in and around the wire hole (seen above in Figure 15). Part of the ends of the wires, around the base where the insulation ends, was also
lightly encapsulated with epoxy adhesive to prevent leaks through the wire insulation during pressurization.

4.2 Pressurization

Many things went into the design process of the pressurization system. The pressurization system is the system created to add pressure to the SMP composite to assist in its deployment.

One of the first things required was to calculate the volume of the fully deployed SMP composite. With the end caps on the tube, the volume is 0.00926 m$^3$. With this information the pressure or amount of gas needed for deployment can be calculated.

Initially using basic thermodynamic equations from the Thermodynamics book [7], calculations to determine how much pressure would be in the tube when a 12 g CO$_2$ canisters fully discharged into the SMP composite tube were done. Pressure in a CO$_2$ canister is at 850 psi = 5860.5 kPa. Using the following equations and EES, at different temperatures the calculated pressure in the SMP composite can be determined.

\[
m_i - m_e = \Delta\text{system} \Rightarrow m_i = m_2 - m_1 = m_2 - 0 = m_2
\]

\[
m_i h_i = m_2 u_2 \Rightarrow h_i = u_2
\]

\[
\rho_2 = \frac{m}{V}
\]

\[
P_{2\text{calc}} = \rho_2 (h_2 - h_i) = \rho_2 (h_2 - u_2)
\]

At 21 °C using ESS, $u_2 = -85.83$ kJ/kg, $h_2 = -41.63$ kJ/kg, and $\rho_2 = 1.296$ kg/m$^3$ the calculated $P_2$ = 63.59 kPa in the tube. This is greater then the 41.37 kPa which is 6 psi. At 20 °C, $u_2 = -251.7$ kJ/kg and $h_2 = -243.2$ kJ/kg which allows a calculated value of $P_2 = 11.05$ kPa. With these results trying to determine whether the initial design would work was difficult as the initial temperature
of the gas was unknown. Taking equation (4) and rearranging the terms to obtain a new equation (5) and using equation (3) allowed calculation of the mass required in the tube to reach 6 psi.

$$\rho_2 = \frac{P_2}{h_2 - u_2}$$

Again using EES and setting the temperature to 25 °C, a value of $\rho_2 = 0.7359$ was obtained and mass required is 6.8 g. At a temperature of -20 °C, mass required is 8 g.

For the actual pressurization system, several ideas were considered. How to store and deliver a gas into the SMP composite was the question. Possible solutions included a high-pressure hose to store the pressurized gas that was connected to the end cap with an electric solenoid valve. This was deemed to require too much power which was not able to be provided in a feasible way. The next idea came when considering CO₂ delivery systems such as for paintball guns, soda water dispensers or rapid inflation pumps for bicycle tires. These systems can use 12 g to 88 g pressurized canisters. The biggest issue at this point was how to tap into the canister and triggering the release of the gas into the SMP composite.

While investigating the rapid inflation pumps, a pump with a threaded nozzle was found. This threaded nozzle was designed to fit a standard Schrader valve stem. These valve stems are found on most bicycle and automobile tires. This prompted the solution of using the Schrader valve stem as the opening through the end cap for the delivery system.
A valve stem as shown in Figure 18 was cut from a bicycle tire along with about a 1 inch of the tire around the stem. Using a size “Q” drill bit, a hole was drilled through the center of the larger end cap. Using 100 grit sandpaper; about a 1 inch radius around the newly drilled hole was roughed up on the SMP composite side of the end cap. The valve stem and tire were also roughed up. Any grit or dust from sanding was washed off and then they were allowed to dry. While the end cap and valve stem were drying, a small amount of epoxy adhesive was mixed. The epoxy was applied to the end cap and the valve stem was inserted through the drilled hole. The end cap and tire rubber were clamped together and were left this way for 24 hours to allow the epoxy full cure time.
From the calculations done, it was determined that there was too much gas to pressurize the SMP composite. With the concern of overpressurizing the SMP composite and possibly damaging it, a way to regulate the amount of pressure in the tube was needed. Two ideas were considered. The first was to use a pressure regulating valve on the valve stem to only allow 6 psi into the SMP composite. The other was to add a pressure relief valve to the bottom end cap. The was no easy way to add a pressure regulator to the valve stem and there was a concern that the regulator would not let in enough gas or at a fast enough speed to be effective in pressurizing the SMP composite. With these concerns that took the pressure regulator out of consideration leaving the pressure relief valve option. A 3/8 inch adjustable brass pressure relief valve was obtained from MCMaster-Carr for this purpose. See figure 17.

To install the pressure relief valve a ½ inch tap was drilled into the smaller end cap and a 3/8 inch female to ½ inch male coupling was obtained. As the pressure relief valve is adjustable, how far the nut is turned determines the amount of pressure it allows through. Using the air pressure line in the lab and a pressure regulator, the pressure relief valve was adjusted to approximately 6.5 psi. As the pressure regulator only had tick marks at the whole numbers as
shown in figure 19 and a pressure of slightly higher the 6 psi was required to allow the 6 psi to
do its work of rigidizing the SMP composite, a more precise adjustment was not needed or able
be done. While still attached to the air pressure line, a quick test of the pressure relief valve was
done. Turning up the regulator to 10 psi and opening the ball valve adjoining the regulator to the
pressure relief valve, allowed for this test. The pressure relief valve did allow bleed off of the
excess pressure and when the regulator was turned to 6 psi the bleed off of pressure stopped. You
could not feel any air coming out of the pressure relief valve and when placed under water no air
bubbles were seen.

Figure 19: Pressure Regulator on air pressure line in lab.

A robotic hand and servo were purchased to cause the triggering of the rapid inflation
system. See figure 17. During testing of this setup the servo cause the hand to trigger the pump,
which was not hooked to the valve stem and steady stream of CO2 came out of the nozzle.
However when doing a whole system test, it was determined that the servo was not strong
enough to cause the valve stem to open to allow delivery of the CO2 into the SMP composite.
After the pressurization system was designed testing of the SMP composite was performed. The testing was to find leaks and ensure the end caps, adhesive and SMP composite could withstand 6 psi. Originally the testing of the SMP composite was to have two separate tests. The first test was to suspend enough weight from the bottom end cap with the larger end cap suspended from a table holding the entire tube and weights off the ground. The second test was to have a hose attached to the smaller end cap with the opening on the hose held 14 feet high. The first test was never implemented as the original concept of looping the weights around the end cap actually did not test the end caps ability to withstand 6 psi. The weight that was determined to be used was 58.6 lbs based on the diameter of the opening of the tube. By hanging the weights off the end cap only the adhesive attaching the end cap to the SMP composite is tested. And less weight would be needed. The second test was determined infeasible when the testing SMP composite sustained irreparable damage and we had to use the larger SMP composite. Since it had been determined that the placement of the heaters in the interior of the SMP composite was ideal for heating and the heaters would have to be placed inside before the end caps were attached them, the water testing could not be performed. This was because there was no easy way to dry the inside of the SMP composite and ensure that the heaters were not damaged from the water. This is when the idea for using the air pressure lines in the lab for testing was proposed.

Using the air pressure line in the lab, a test for leaks in the SMP composite, the end caps and the adhesive between the end caps and the SMP composite was performed. Figure 20 shows the set up of this test before placing the SMP composite into the tub of water. This test also helped determine if the end caps, adhesive and the SMP composite could withstand 6 psi. The smaller end cap was hooked up to the air pressure time and 6 psi of air was allowed to flow into
the SMP composite. The only leaks found were between the wires and their plastic insulation. The wire are for the heaters and were inserted through and epoxied to the larger end cap. After mixing a small amount of quick set epoxy and applying it to the very edge or the insulation next to the exposed wire and letting it set the tube was tested again. This time there were no leaks. The pressure regulator was then turned up to 10 psi. There was no change in the SMP composite, end caps or where the adhesive was attached. Opening the valve stem allowed the bleed off of excess air and pressure in the SMP composite.

Figure 20: SMP Composite hooked to air pressure line in lab.

4.3 Payload box

A box of some sort is needed to transport the entire deployment system into the near space environment when the balloon is launched. There have been 6 iterations of the payload box since inception. The first was designed to hold the entire SMP composite and equipment to run the experiment. Since the purpose of the experiment is to approximate a space-based deployment, the SMP composite needs to be exposed to the near space environment. This means
no box around the SMP composite. Therefore the second iteration was a smaller box (8”x8”x8”) to hold the electronics. This box has a circular hole in the bottom for the SMP composite to hang from and legs hanging from the corners of the bottom of the box that run down to a base as a way to surround the SMP composite. The third iteration had a large cutout that allowed the insertion of the SMP composite with the end caps attached. The fourth iteration modified the circular hole by making it a square just large enough for the smaller end cap to fit through. All four of these iterations designed using ¾ inch Dow Thermax insulation panels [8]. The Dow Thermax insulation was chosen as the walls of the box because it is designed to operate in the given temperature range and can help keep the electronic equipment from getting too cold.

The fourth iteration was created using ¾ inch Dow Thermax and used Aluminum angle for the legs and base. This gave a nice, sturdy, over designed box that could rest on the base. The next iteration was to make it such that it could survive a parachute landing instead of a 40 mph drop. This involved using ½ inch Dow Thermax insulation and using tape measure for legs and Aluminum angle for the base. The tape measure was chosen for the legs because it is lightweight and can buckle. This is handy when the box lands, the buckling can absorb some of the shock of the impact with the ground.

All six sides of the box were cut out of the ½ inch Dow Thermax, covered in MonoKote and glued together. Four small pieces of aluminum angle were cut to attach the tape measure to the box for the legs. Then four pieces of 8 inch long Aluminum angle where cut and drilled and attached together and then were attached to the tape measure legs. A stand was created to hang this box on since the legs could not support the weight of the box.

Once the pressurization system was decided upon and created, a test fit in the box was done. This shown that the box was too small thus requiring a sixth iteration. This iteration kept
the existing legs and base however was bigger. It was 12”x8”x8” instead of 8”x8”x8”. This extra 4” in length allowed the pressurization system to fit into the box. Figure 21 shows the interior of the box where a shelf was added to hold the battery and electronic switches. Again the box was made out of ½” Dow Thermax insulation and covered in silver MonoKote.

With this last design iteration, a strapping system was designed to assist in hooking the payload box to the parachute and the command module for the flight as seen in Figure 22. The strapping is 1” green nylon webbing with 8 D-rings placed on all four sides. 4 D-rings are placed on the short side so that they are inline with the top edge of the box when the straps are clipped together, while the other 4 D-rings are inline with the bottom of the box on the long side. The straps are sewn together using green polyester wrapped cotton string.

![Figure 21: Interior of box with shelf.](image-url)
Figure 22: Payload box with tape measure legs, balsa wood base, and strapping system.

When the entire system was taken to the scale and weighed it was determined to be 3 lbs over the weight limit. One of the ways to help reduce this weight was to remove the Aluminum angle from the box. The brackets used to hold on the legs to the box were replaced with plastic angle. The base itself was replaced with 3/32 inch balsa wood. By removing these items, ½ lb of weight was able to be saved.

4.4 Characterization

4.4.1 Initial Planned Approach
The initial approach for characterizing the length of the composite before and after deployment was to use photogrammetry to create a 3D shape of the composite. By comparing the before and after shapes, the accuracy of the deployment would then be assessed. The next planned detail for characterization was to perform the picture taking for photogrammetry in flight.

Photogrammetry is a technique for creating and measuring 2D or 3D models of an object using photo-grammes. Photo-grammes are photos of the object from multiple views using high resolution digital camera. The object in the photo-grammes is often marked with many circles contrasting in color to the background color of the composite material. Figure 23 below shows the basic concept of photogrammetry: triangulation of multiple points on the surface of an object.

![Multiple point triangulation](source: http://www.geodetic.com/WhatIs.htm [9])

In order to achieve the most accurate model possible, photo-grammes should be taken from multiple views of the composite in a given shape. If the same camera is needed to take the
pictures then a mechanism that allows for translation a single camera to multiple locations needs to be developed. If the same type of camera, but not the same exact camera can be used, then two or three digital cameras need to be mounted in the payload box at strategic locations so sufficient photos can be taken for photogrammetry. As a matter of proper experimental procedure, the composite should be characterized in the payload box before initial packing, in the same method that the composite will be characterized at altitude.

4.4.2 Discussion

The first step taken for characterization was to determine the type of digital camera that was to be used. Typically, a higher resolution camera indicates a higher attainable accuracy of characterization, but higher resolution also means higher cost. Cameras that were initially investigated were 10mega pixel cameras at a cost of around $300 per camera. As the budget became tighter, the option of using cameras this costly was quickly abandoned. 4.1mega pixel cameras are generally considered to be the lowest resolution camera that would provide reasonable characterization accuracy (with in 3-5mm). In researching cameras, it was found that 5.1 mega pixel cameras are relatively cost effective and above that minimum threshold for digital characterization cameras. As a result of these findings, the camera selected for use was a Fujifilm FinePix A500.

The initial design proposed for characterization was to mount three cameras in the payload box that would take pictures of the composite in its deployed form during flight. However, minimum recommended angles of 10° to 15° with respect to the vertical axis would mean a box chamber that would be approaching 1ftx1ftx1ft. This extra material for the box in addition to each camera and timer circuit assembly weighing approximately 0.5lb would have
not allowed for adequate room in the box for other essential items while still remaining under the weight limit of six pounds. As a result, other measures needed to be taken.

The first change that was made to the original plan for characterization was to focus more on measuring the straightness of the composite rather than looking at the entire shape of the composite. This simplified the final design, and allowed for options other than photogrammetry to be considered for characterization.

Upon determining that the straightness of the composite was the focus for characterization, targets that would be used for photogrammetry could be determined. The basic design for the target was to use a stencil to paint an “x” on the point where the target was desired to be, using rustoleum spray paint. To be able to orient multiple pictures in Photo Modeler Pro 5 [10], methods for identifying points from picture to picture needed to be created. The solution for this was to create control points. The control points would consist of the previously marked “x” with a “O” surrounding it. The “O” would be painted in different colors to identify different control points. The targets were painted on the composite bottom end cap and the base of the payload box. This would allow for obtaining the distance of the end cap from the payload box base at multiple points, thus allowing for the determination of the difference in straightness of the composite before and after deployment. Pictures of the stencils and targets are below.

Figure 24: Stencils used for painting targets
In trying to retain the option of using photogrammetry, one proposed option was to use mirrors to capture an extra view of the composite. This idea was attempted, and pictures of the targets on the end cap relative to the base were obtained. Even in using two cameras with a mirror providing a third view the photos could not be processed by the software. The two problems that the program was having were that the targets in the mirror were in a different location, calling the points in the mirror miss-referenced, and too low of angles of the pictures with respect to the vertical axis. The procedure for photogrammetry begins by orienting all of the
photos with each other. Then the targets are marked and processed based upon the initial orientation. So using a view with a mirror confused the program and the images did not process. Designing the system to work to this method would result in that using three cameras as initially planned would actually be the better method in labor and weight.

4.4.3 Final characterization design

This led to the final characterization approach. It was to use photogrammetry as a ground based form of characterization. The in-flight characterization used a single camera to capture an image of the bottom end cap relative to the tape measure legs using a mirror. The image was formed in the mirror of the end cap relative to the tape measure legs and the picture was taken by a camera in the box through the upper end cap. Pictures showing the location of the mirror and a characterization photo are shown below.

![Figure 27: Mirror location for in-flight characterization](image)
Ground based characterization used photogrammetry. The design for this was to place the composite on a poster with targets and control points and take pictures at 8 different views of the composite on the poster. The poster was used to ensure that the composite was placed in a relatively same location before and after deployment and to orient all of the images with each other on a consistent basis. Control points were painted on the poster at each corner and a target was painted mid length on each side of the poster. Additional targets were painted on the top (bigger) end cap as well. This would allow for point to point measuring, thus obtaining the length of the composite at multiple points before and after deployment. The poster, targets on the upper end cap, multiple views are shown below.
Figure 29: Poster used for ground based photogrammetry

Figure 30: Upper end cap, showing the targets painted in each corner
These images are then put into Photo Modeler Pro 5 and processed to produce a 3D representation of all of the control points and targets. These 3D points can be seen below. A scale is created in the program by referencing the actual distance between two targets. This then allows for measuring of the composite length at multiple points in the software.

Figure 32: Targets in 3D space processed using Photo Modeler Pro5

4.5 Stowing (Packing)

4.5.1 Initial planned approach

The initial approach for stowing (packing) the composite was simply to fold the composite along the z–axis (length of the composite tube). This type of folding was easy to determine as the best known way due to the end caps that would be on the composite, preventing
rolling of the composite tube for stow. The next step was planned to be design and fabricate the device (herein after “jig”). Upon fabrication, experimentation in to stowing could begin.

4.5.2 Discussion and final approach/design

The actual process taken for developing the stowing methods closely resembles that which was originally planned. Knowing that z folding was the best known way to fold the composite tube, considering that there would be end caps, the dimensions of the folded composite needed to be determined. For stow, the composite would be flattened before folding. This means that the width of the composite while stowed would be approximately half the circumference of the composite tube. For a tube of roughly 4inches in diameter, the circumference would roughly be 12inches and half of that would be six inches. Due to the design of the end caps, at least one of the dimensions in the hole for the composite to pass through in the payload box needed to be less than 4inches. Considering that the composite was already going to be 6inches wide not mater what length of fold is used, the length of the fold was limited to 4inches. In allowing for the thickness of the composite and various irregularities that may occur with the composite during folding, the fold length was designed to be 3.5inches.

There are numerous jig designs that could be created for folding the composite. One of the more complex designs considered was a concept that would use a folding legs type of assembly. This design concept was inspired by a clothes rack used for air drying clothes. This design ultimately was not used due to potential problems with not being able to maintain a consistent fold.

The design that was determined to be the simplest, through advice from a project advisor, was to use a peg board concept. This concept is a wood board with holes drilled in it to the same diameter of the pegs that would placed in the holes. ½” Pegs would then be cut and would then
be able to be inserted into the holes and removed from the holes. The reason for choosing \( \frac{1}{2}'' \) is that the minimum recommended stowing bend diameter of \( 5/16'' \) was recommended by ILC Dover. In considering which pegs would provide a conservative repeatable bend, and would be easiest to work with \( \frac{1}{2}'' \) diameter pegs were chosen.

The stow process for this design would be to first heat the composite to the required stow/deploy temperature of 70°C, then with all of the pegs removed from the board, place the heated composite on the board and flatten it using a vacuum pump or by pressure from squeezing with hands if the composite wasn’t sealed. After flattening, the first peg would be placed in its hole and the composite folded around that peg. Following that, the next peg would be placed and the composite would be folded around that. This process of inserting and would be repeated, while reheating the composite in a laboratory oven as necessary. A picture of the peg board stowing device is shown below. Also shown below is a short sequence of photos showing the folding of a test composite, also provided by ILC Dover.

![Figure 33: Peg board stow jig](image)
Figure 34: Stow sequence for smaller trial composite (with out end cap)

During the process of stowing some issues arose. The first was associated with the end caps on either end of the composite. The end caps cause the composite to locally want to retain the circular shape that it was glued in. As a result, as the composite is flattened and folded during stow, sharp creases form in the composite. An example of such a crease can be seen above in Figure 33. Severe creases leave a permanent effect on the smp composite. It is evident where the creases were previously, and the composite will tend towards creases previously formed during any subsequent stows. In trying to prevent these creases, stowing became a person task during the first step of flattening of the composite. This step was altered so that one person would be
helping the composite to form in such a way that would discourage creases, while the other person would slowly open the vacuum valve that would engage the vacuum pressure causing the composite to flatten.

4.6 Autonomous beginning and ending of experiment (Chris Beyers)

The heating of the SMP was done with 6 resistive heaters positioned on the inside of the tube with two atop one and other and 120° separation between the three groups. Each group of heaters was controlled by a temperature controller which was set to 84° C. The temperature controllers would work by having a three wire thermistor coming out of it and attached to the composite. Once that thermistor hit 84° C it would cut power to the heaters until the temperature came back down to within 4 or 5° of the set point. This regulated the heating and kept it from continuously heating and possibly destroying the composite. The method of supplying power to the heaters was an 18V lithium-ion battery. To incorporate a switching on function at the proper altitude and keep the 18V battery from being drained right from the launch a solid state relay was added. This relay was connected to the basic stamp and only required 3.5V to switch on. This was achievable because the basic stamp’s high on an output pin is about 5V.

![Figure 35: Robotic hand with servo.](image)

Pressurizing the SMP was attempted by using a servo (similar to the kind that would be seen on a small robot) attached to a timer circuit and a clamp holding a CO2 canister with trigger. The concept and use of the pressurization was again to use the basic stamp to turn on a
“switch” that would then allow the timer circuit being used to continually send out pulses to the servo which would in turn squeeze the clamp holding the CO2 trigger thereby pressurizing the composite. The servo being used took a maximum of 6V pulses and was connected to a simple timer circuit consisting of a 555 timer and a relay. The power to the timer circuit was 12V and was integrated with a TIP102 transistor as the “switching” element. Since the base of the transistor only took 6mA to cause Vce to saturate a resistor of 475 Ohms was added to the output of the basic stamp that switched on the pressurization. This sank down the current that triggered the switching to 10.5mA allowing for a smaller amount of power drain from the Basic Stamp’s battery while still serving the function at hand. Once the switch had closed the pulse interval of the timer was every 2.5 seconds, which was the fastest we could create using the timers we had. Using 6V to power the servo it was found that sometimes it was enough to squeeze the CO2 trigger and pressurize and sometimes it was not. This led to the conclusion that a larger servo was needed.

The characterization of the SMP was done using a digital camera hooked to the same type of timer circuit that was used for pressurization. To connect the correct leads to the digital camera to make it take pictures the camera had to first be opened. After the camera’s case had come off the method of finding which two leads were needed was using a multimeter to find the change in connectivity in leads around the picture taking button when the button had been pushed. The tricky part about this is that the camera we used had an auto focus that engaged when the button was pushed halfway down and then the picture was actually taken when the button was pushed all the way down. To solve this problem wires were taken from all three leads and the picture and focus lead were tied together. When the power lead touched the two tied together it focused and took a picture which solved our problem. In terms of making this
camera start taking pictures at a certain altitude the plan was to wire it exactly like the
pressurization circuit using a transistor and basic stamp. While doing this we ran into the
problem of the camera shutting off after a period of inactivity, so by the time the balloon was at
altitude and the stamp sent a signal to start taking pictures the camera would be turned off and
there would be no pictures taken. To solve this problem a mechanical switch was put in place of
the stamp/transistor switch and when the balloon was ready to be launched we would flip it on
starting the timer circuit and continually taking pictures throughout the entire flight. This was
deemed the fastest and easiest way to solve the problem with only needing to acquire a larger
memory card.

The following is a circuit diagram of all electronics used for the SMP pressurization,
characterization, and heating.
4.7 System Experimentation and flight simulation

4.7.1 Integration of heating system and heating trigger

The first step in putting all of the systems together was to hook up the two different batteries in two different trials to the heater system and to the triggering design. The circuitry for this is shown above. The basic design is to connect a solid state relay to the microprocessor and to the battery. The microprocessor will send a signal to open and/or close the circuit to the battery. In testing how the different components worked together in this step, the temperature distribution in the composite for each battery was also obtained.
The first trial used the 18V, 3.0Amp-hour battery. The thermocouples were placed in between the heater strips (the midpoint in between the heaters around the circumference of the composite). One other thermocouple was placed 1 inch from the end of the heater strip, and the final thermocouple was placed at the bottom of the composite (right next to the end cap) in between the heaters. This final thermocouple was in the location pre-determined to be the "cold spot". This test was performed in the vacuum chamber, and the resulting temperature distribution and current output of the battery is below.

One observation noticed for this trial is that the heaters take a period of time to reach a steady state current. This was determined to be a result of the heaters changing in resistance as they warm up, thus causing a change in current. In the case of this trial, steady state current was reached after 6 minutes. Using the best fit curve the integral of the current with respect to time was taken from the initial time to the final elapsed time for the experiment. This number turned

\[ y = -72043x^5 + 52021x^4 - 14074x^3 + 1767.2x^2 - 105.31x + 8.4827 \]
out to be 1.52 Amp-hour, as compared to the 3Amp-hour rating for the battery. This essentially means that the battery was only being used at 50% capacity.

The temperature distribution in the composite was not what was required in the design criteria. As can be seen one of the thermocouples has an abnormal temperature profile. This is the result of the thermocouple falling off during the experiment. As a result of the temperature distribution seen above, the initial summary of the use of this battery was that it was not sufficient for heating the composite to deployment.

The trigger design was tested in this trial by hooking the microprocessor up to a laptop computer and sending the microprocessor “false signals” meaning that altitudes were being fed to the microprocessor to make it sense that it was at altitude. This designed worked with out flaw, thus proving its flight readiness.

Figure 38: Temperature versus time for 18V battery heating
The next step was to hook up the 28V battery and run the previous trial over again, in the exact same manner as before. The current output by the batteries is of similar form, only increased.

![Current Output vs Time](image)

**Figure 39: Current output of 28V lithium ion battery**

The steady state current for this battery was approximately 7Amps. The expected time duration of this battery is then approximately 24-25 minutes based on the 3amp-hour life.

The temperature distribution from the 28V battery is shown below. As can be seen the temperatures are overall much higher than the 18V battery can provide. Using this battery would provide more than enough power for deployment. It actually would be a case of taking much precaution to ensure there is too much power provided to the composite. In this trial the power to the heaters had to be shut off due to concerns of reaching that maximum allowable polymer temperature of 120°C.
Based upon the above results, the 28V battery would be the best option for flight if weight were not an issue. This particular battery weighs 2.4 pounds as compared to 1.4 pounds for the 18V battery. For these reasons it was decided to further investigate the 18V battery in deploying the composite.

4.7.2 Composite Deployment using in-flight power source

For this experiment, the viability of using the 18V to deploy the composite was investigated. First the composite was stowed using the stowing jig, and the composite was placed in the vacuum chamber with controllers, heaters, microprocessor analogue (a mechanical switch), solid state relay, and 18V lithium ion battery hooked up. A picture showing the equipment outside of the vacuum chamber is shown below.
The experiment was run and results were that the composite does deploy using the 18V battery. This encouraging since the power required to heat the composite in the vacuum chamber and the power required to heat the composite during flight are within 10W of each other. This shows viability for the 18V lithium ion battery to be used for flight.

The pre-stow, stowed, and deployed pictures of the composite are below. Ground based characterization results show that the composite was actually longer by 2mm - 4mm after deployment. This error can be a result of a couple items. First, there is error in marking the points with in each photograph. Having the targets be off by 1mm-2mm is possible due to the type of targets being use. The width of the line used in the “X” was more than 2mm. which would allow for at least a 1mm variation per target. Then having this occur on multiple targets propagated through an angle could very likely result in a difference on 4mm in length from measurement. The second way that this error could have occurred is that this is a material issue with the smp composite. It could be that thermal stresses were relieved or that deploying with gravity caused the composite to elongate even more than its original shape. In a scenario such as
this it would have been useful to have the time to run the photogrammetry for shape of the composite to determine if there were any Poisson effects.

<table>
<thead>
<tr>
<th>Pre-Stow</th>
<th>Stowed</th>
<th>Deployed</th>
</tr>
</thead>
</table>

Figure 42: Pre-stow, stowed, and deployed configurations for deployment with 18V battery

A video of this deployment is attached in a CD-R appendix.

4.7.3 Weight Considerations

In assembling all of the systems in the payload box the system weight was obtained. The weight of all systems at this point was 9 pounds. At this time the characterization design was using two timer circuit/camera assemblies. Also included in this were the 28V battery, the pressurization system, and some aluminum hardware that was on the payload box at that time. By switching the aluminum base of the payload box to balsa wood and changing aluminum brackets to plastic brackets, half a pound was saved. By using the information that the composite deployed using the 18V battery and no pressurization system, one pound was saved by switching to the 18V battery and another pound and a half was saved by doing with out the pressurization system for flight. This put the system right at the six pound weight limit.

4.7.4 Simulated flight

In showing proof that they system was flight ready, a simulated flight was conducted in standard temperature and pressure assuming that the nine pound load could be flown. This test included the use of the pressurization system and the 28V battery. Knowing that convection had

- 54 -
affected heating of the composite before was the reason for using the 28V. Theoretically the steady state power output of the 28V battery was 195W and the power required for full deployment in STP was 217W, thus the system did not have enough power to fully deploy. However, this was the only option for testing due to the size limitations associated with the vacuum chamber on hand and readily available for use.

The test was initiated by running through set up and hook up of all systems. First the composite was stowed using the stowing jig. Then it was mounted in the box such that it was bent away from the mirror on the base of the payload box. The composite was then bolted into place using nylon 3/8” diameter bolts. The heaters and thermistors were hooked up to the controllers and power leads hooked up to the controllers. The controller set points were then set to 84°C. Then the quick inflator with handle extension and servo were attached. After that the HOBO type t thermocouple temperature data loggers (being used for in-flight data recording) were initiated placed in the box. The thermocouples were affixed to the composite via a bandaid (for insulation) and a piece of gorilla tape. The piece of tape was approximately 4square inches so as to ensure the thermocouple would not come off of the composite. Then the camera was mounted on the end cap using two pieces of ¾” dow thermax insulation wrapped in tape as stands for the camera to sit on. The camera lense would strike the end cap any other way, or the camera would be resting on the lense, which is not good for the integrity of the camera.

The camera was turned on and fixed into place using strips of gorilla tape. Due to the nature of the camera, it would turn off after a period of in activity (ie. it would turn off during flight). The timer circuits and triggering design do not have the ability to turn the camera on, they are only able to initiate taking of pictures. Other cameras have the ability to be remotely operated such that they could be turned on and operated from ground station, but this technology
is too costly and too heavy for this system at this point. As a result, the cameras were turned on and picture taking was initiated before the box was closed.

Once the camera was mounted and turned on, the shelf was placed inside of the box and the battery was placed on the shelf and hooked up to the solid state relay and power leads to the heaters. Then the timer circuits for pressurization and characterization were placed on this shelf as well. The box was then closed up and a signal sent to the microprocessor to begin. Pictures of the inside and out side of the box are below.

![Internal view (not pictured, shelf with battery, timer circuits and solid state relay)](image1)

![External view](image2)

**Figure 43: Internal and external views of the box with systems mounted in place**

The systems being used for flight worked well. The only issue was a setting on the camera that made it focus on items up close to it rather than farther away such as in the mirror on the base of the payload box. The temperature versus time from the HOBO temperature recorders is below.
As anticipated, the composite did not fully deploy due to convection. This case is evident in that the top of the composite, which gets warmer than the bottom during heating in convection, was deployed more than the bottom. A picture of the composite for pre-deploy, stow, and deploy is shown below.

![Pre-stow, stowed, deployed composite](image)

**Figure 45: Pre-stow, stow, and deploy for simulated flight test**

A video of this deployment can be seen on an attached CD-R appendix.

### 4.8 Launch

#### 4.8.1 Prep for launch

*(weather, flight prediction, and notice to faa)*

One of the basic steps for preparing for a launch is checking the weather. This includes checking the forecast for the percentage of cloud cover, ground level winds and atmospheric winds for the day of the launch.
About a week before a possible launch date go to the Weather Underground website[11] at http://www.weatherunderground.com. Type in the zip code of a launch site and click on the magnifying glass. Once that page loads click on the latest day of the 5-day forecast, a new page will load and you will need to click on the word details for the day of the potential launch. This page will show the forecasted weather for the launch date including percent cloud cover and ground level winds at 1am, 7am, 1pm and 7pm during regular hours and 2am, 8am, 2pm and 8pm during Daylight Savings hours, such as can be seen in the figure below. Under the 7am or 8am column record the percent cloud cover and ground level winds including direction. This time is closest to our launch window of as close to dawn as possible. This will be done for each possible launch site. This will also need to be done each day until the day before the launch. This also allows a way to get a feel for what the weather may be like a few days ahead of time. By about 3 days before the launch date a determination of whether or not the weather will be good enough for a launch can be made.
Figure 26: WeatherUnderground Detail Forecast for Tuesday March 13, 2007 at New Castle, Indiana 47362

If the weather, according to the Weather Underground website, is favorable go to the University of Wyoming’s weather website Wyoming Weather Web [12] at http://weather.uwyo.edu/ and click on Forecast from Numerical Analysis, then on GFS model. This page will allow checking the forecasts of many different things about the weather, specifically the upper atmosphere winds. In the first column click on the radial labeled Winds, in the second column, None. In the third column click on Winds Speeds and the fourth click on None. The fifth column is optional however clicking on Wind Arrows is recommended. Under
Forecasts choose the time that corresponds to the time and day of any potential launch. Then under level choose 400 to 150 mb and click Get Data. This will give a map of the United States with the wind speeds labeled and if you choose the option for the Wind Arrows, the direction of the wind. See Figure 47. As long as there are no speeds over 100 knots over Indiana and Ohio then the launch can proceed. Contact the airport management at the airport chosen for launching to obtain permission to use the airport.

![Figure 47: GFS Output from Wyoming Weather Web](image)

Keep checking both Weather Underground and Wyoming Weather Web to confirm that no significant change in the weather has occurred. The day before the launch check with NOAA for the wind soundings to confirm wind direction and speed. Any points over 120 knots or more then 5 points over 100 knots will cause the launch to be canceled. The easiest way to check the
wind soundings is to run a flight prediction with the software on the project laptop. The Predict v4.0 flight prediction software on the laptop automatically pulls the wind soundings from NOAA for Wilmington, OH (ILN) and White Lake, MI (DTX) and place the file on the desktop.

The last major item to be completed before a launch is to notify the FAA between 8 to 24 hours before launch time. Then the evening the day before the launch using the 000Z day of the flight winds soundings from NOAA using BalloonTrak run a flight prediction and use prediction to fill out the NOTICE to FAA form. This form is then faxed to the nearest FAA ATC Facility and the student who faxed it will call and confirm that they received it. The nearest ATC facility is the Dayton International Airport. The fax number and the voice number are located on the NOTICE to FAA form. After the launch of the balloon, contact the ATC facility to let them know the time of the launch.

In addition to these items mentioned above a preparatory checklist, a parts checklist, and launch procedure must also be followed. This list can be found in Appendix I.

4.8.2 SMP composite in-flight deployment

This portion of the project was not completed by the close of Winter Quarter 2007. The two main reasons for this is that the amount of work that needed to be done was not properly anticipated and the weather did not line up for the days in which the team would be ready to launch. The simulated flight was completed by March 4, 2007 leaving almost an entire week for launch, but weather just did not cooperate.
5. Schedule
The schedule is presented below, in Gantt Chart form. The blue lines are the initial and the red lines are the actual. In general as can be observed, most areas of the project started on time, but they just took much longer than anticipated.

### Table 4: Original versus actual schedule

<table>
<thead>
<tr>
<th></th>
<th>Fall Quarter</th>
<th>Winter Break</th>
<th>Whole Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choosing Project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brain Storming</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forming Team</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Launch, Track &amp; Retrieve ability improvement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) Improve command module design (EE’s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) Develop payload box</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) Develop and integrate heating method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.1) Qualitative Testing of material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.2) FEA/Modeling of heat transfer to composite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.3) Initial investigation into smp composite heaters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.4) Investigation of power sources</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.5) System Level Testing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5) Develop and integrate pressurization method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6) Develop and implement characterization method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7) Experimental testing</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|                  |              |              |               |
|                  |              |              |               |
|                  |              |              |               |
|                  |              |              |               |
|                  |              |              |               |
|                  |              |              |               |

6. Cost
Below is a table summarizing the planned cost versus the actual cost. Main areas that costs were more than anticipated were the pressurization and heating. The change in approach for the heating system caused the purchasing of many more heaters than planned for and as a result the cost for the heating increased. A spreadsheet of items purchased can be found in Appendix II.
Table 5: Summary of project expenses

<table>
<thead>
<tr>
<th>Area</th>
<th>Planned</th>
<th>Actual</th>
<th>Allotted</th>
<th>Overspent</th>
</tr>
</thead>
<tbody>
<tr>
<td>General program expenses/2</td>
<td>$925.00</td>
<td>$933.20</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SMP deployment project</td>
<td>$1,550</td>
<td>$4,055.30</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,475.00</strong></td>
<td><strong>$4,988.50</strong></td>
<td><strong>$4,750.00</strong></td>
<td><strong>$238.50</strong></td>
</tr>
</tbody>
</table>

7. Acknowledgements

This project was significantly aided by the following institutions or individuals. Much appreciation is extended to them for their assistance with the project.

Ohio Space Grant Consortium
   For providing project funding.
ILC Dover
   Designed and manufactured composite boom provided to team.
WSU Physics Dept
   Provided the vacuum chamber used for experimentation.
Cornerstone Research Group Inc.
   Provided various equipment for use, including vacuum pump used with vacuum chamber.
Dr. J. Mitch Wolff and Dr. Joseph C. Slater, PE
   Served as project advisors.

8. References and Bibliography

References

6. (2007). “Adept Scientific”. Adeptise. [Internet WWW]. Address: [www.adeptscientific.co.uk](http://www.adeptscientific.co.uk); [25 December 2006].

Bibliography

1. “Adept Scientific”. Adeptise. [Internet WWW]. Address: www.adeptscientific.co.uk; [25 December 2006].
10. Scarborough, Stephen E., Cadogan, David P. “Applications of Inflatable Rigidizable Structures.” Frederica, Delaware: ILC Dover LP
11. “Shape Memory Polymers – A Short Tutorial”. Cornerstone Research Group Inc. [Internet, WWW]. Address: http://www.crgrp.net/tutorials/smp2.htm; [Accessed 7 March 2007].


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9. Appendix I

Balloon Launch checklist

PREPARATORY CHECKLIST

Preflight Planning

___Weather Checks Completed
___BalloonTrack Prediction Okay
___Launch Site Confirmed
___Launch Team & Chase Team Personnel Totals
___Gas Cylinder Transport Arranged
___FAA Contacted
___Airport Contacted

Preflight Systems

___Gas Fill Team
   ___Balloon Available
   ___Full Helium Cylinders***QTY___
   ___Fill Valve Ready
   ___Equipment Ready
   ___Flight Crew Available

___Imaging/Cameras
   ___Camera(s) Functioning
Memory Available
Batteries Charged
Flight Crew Available

Communications
Radios & GPS Functioning
Screamer Functioning
Laptop Functioning & Power System Ready
Batteries Charged
All Wires Securely Connected
Flight Crew Available

Payload
All Flight Boxes in Good Condition
Experiment in Working Order
Experiment Data Collection Working
Connections Between Modules Secure
Flight Crew Available
PARTS CHECKLIST

- Ground cloth/tarp
- Weights for ground cloth
- Table
- Handling gloves
- “Big hands”
- Helium (in secure transport structure)
- Helium regulator
- Balloon hose and filler assembly
- Filler assembly hose clamp
- Fish scale/counterweight
- Balloon
- Parachute
- Kite string cut to length
- Carabiners
- Knitting hoop
- Handheld GPS tracker
- Notebook and pen
- Video camera and battery
- Video camera cassettes
- Digital camera and batteries
- Snacks and beverage
- Mobile HAM (with car battery)
- Directional antennae
- Ham radios used with directional antennae
- AA batteries for directional antenna radios
- Walkie-Talkies to be used during foxhunting
- AAA batteries for walkie-talkies
- Laptop
  - Power cable
  - Floppy drive
  - CD-ROM drive
  - Drive cable
  - HAM→PC cable
  - HOBO Cable
  - Wireless card
  - USB flash drive
  - Camera card reader
- Communication module
  - GPS receiver
  - GPS antenna
  - Battery pack (for GPS) – 4 AA batteries
  - Handheld HAM radio with battery pack
  - HAM antenna
  - Screamer circuit
- 9V battery for screamer
- “SOS” foxhunting beacon
- Camera
- Camera batteries
- Camera flash memory card
- HOBO logger
- Thermocouple
- Box lid
- Nylon bag
- Bag label card – harmless radio device; contact info
- hand warmers
- carabiners to attach to bottom of command module

☐ Experiment module
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________
  - ________________________________

☐ Tool kit
  - Multimeter
  - Screwdrivers
  - Pliers
  - Wire cutters
  - Wire
  - Electrical tape
  - Duct tape
  - Spare AA batteries
  - Battery charger
  - Spare 9V batteries
  - Zip ties
  - Kite string
  - Pocketknife
  - Scissors
  - Extra carabiners
Launch Preparation Procedure

1. Payload and parachute weight: ____________________ lbs
2. Desired lift: $1.2\left(#1 + m_{\text{balloon}}\right) - m_{\text{balloon}} = ____________________ lbs$
3. Check gas level in cylinders to be used
4. At launch site
   a. Place ground cloth on ground with no sharp objects (weight down corners)
   b. Attach regulator to cylinder #1
   c. Make sure regulator output closed
   d. Note Initial pressure of cylinder #1: ______________ psi
   e. Put on handling gloves
   f. Place balloon on ground cloth, inspect for damages
   g. Tape lift gauge loop to filler assembly
   h. Place balloon nozzle over filler assembly
   i. Clamp or tape balloon nozzle onto filler assembly
   j. One person should be holding the balloon nozzle, one person operating the regulator, others guarding the balloon with “big hands”
   k. Begin inflation (use regulator to begin slowly and increase fill rate as balloon takes shape)
   l. When cylinder #1 reaches ~100 psi close regulator output
   m. Record cylinder #1 pressure: ______________ psi
   n. Shut off in-line valve
   o. Shut off cylinder #1 valve
   p. Move regulator to cylinder #2
   q. Open cylinder #2 valve
   r. Record cylinder #2 initial pressure: ______________ psi
   s. Open regulator
   t. Open in-line valve, continue inflation
   u. When appropriate, connect fish scale to loop
   v. Carefully let go of balloon nozzle while someone holds fish scale
   w. Take several readings and roughly average in your head
   x. When desired lift achieved, close in-line valve and regulator
   y. Record final pressure of cylinder #2: ______________ psi
   z. Close cylinder
   aa. Tape load loop to balloon nozzle with small piece of tape
   bb. Pinch off balloon nozzle
   cc. Twist balloon nozzle
dd. Tie balloon nozzle with kite string (CAUTION: not too tight or it will tear through)
ee. Fold nozzle material
ff. Tie again
gg. Duct tape balloon nozzle
5. Check connections
   a. Flight GPS antenna to GPS unit (before power-up)
   b. Flight GPS to flight HAM radio (Kenwood TH-D7)
c. Batteries to GPS unit
d. Flight HAM radio to HAM antenna
e. HAM radio battery pack
f. Camera batteries
g. Camera timer circuit
h. Camera timer circuit switch
i. Screamer speaker
j. Screamer circuit
k. Screamer battery
l. Screamer switch
m. HOBO thermocouple

6. Prepare laptop/mobile HAM radio
   a. Power on laptop
   b. Power on HAM radio
   c. Connect to mobile HAM radio
   d. Set HAM frequency to 144.390 MHz
   e. Check TNC mode
   f. Check APRS mode
   g. Load Xastir

7. Check settings
   a. Power on HAM radio
   b. Set frequency to 144.390 MHz
   c. Check TNC mode
   d. Check Beacon mode
   e. Lock keypad (hold F for >1s)
   f. Confirm receiving signals in Xastir
   g. Move communication module around, checking that Xastir updates location

8. HOBO launch
   a. Close Xastir (serial port is needed to launch HOBO)
   b. Connect HOBO cable
   c. Launch HOBO logger
   d. Delete log file in Xastir log folder
   e. Reopen Xastir
   f. Reconfirm data reception
   g. Start trace on callsign
   h. Confirm that coordinates are reasonable by comparing with handheld GPS

9. Check experiment module operation
   a. __________________________
   b. __________________________
   c. __________________________
   d. __________________________
   e. __________________________
   f. __________________________

10. Camera
    a. Turn on camera
    b. Turn on timer
c. Confirm pictures are being taken
d. Make sure the display is off
11. Switch on screamer circuit
12. Final check of APRS packet reception
13. Begin APRS packet logging
14. Connect parachute to balloon (redundant strings)
15. Connect parachute to hoop
16. Connect hoop to communications module
17. Connect communications module to experiment module
18. Launch

CONTACT SHEET AND DIRECTIONS

Contact Names and Phone Numbers:
Appendix II – Cost spreadsheet

General expenses for the program are listed below. The smp composite project is responsible for half since there are two separate teams in the HAB program this year.

<table>
<thead>
<tr>
<th>Product</th>
<th>Vendor</th>
<th>Price</th>
<th>Shipping</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x 244 cu. ft. tanks Helium (2 tanks=2*36.75)</td>
<td>WSU - through Greg Wilt</td>
<td>$73.50</td>
<td>$0.00</td>
<td>$73.50</td>
</tr>
<tr>
<td>Linksys® Wireless G notebook adapter</td>
<td>Best Buy</td>
<td>$64.99</td>
<td>$0.00</td>
<td>$64.99</td>
</tr>
<tr>
<td>Balloon (1500 gram, qty 1)</td>
<td><a href="https://secure.scientificsales.com/Details.cfm?ProdID=129&amp;category=8">https://secure.scientificsales.com/Details.cfm?ProdID=129&amp;category=8</a></td>
<td>$125.00</td>
<td>$12.90</td>
<td>$137.90</td>
</tr>
<tr>
<td>men's brown jersey glove</td>
<td></td>
<td>$2.68</td>
<td></td>
<td>$2.68</td>
</tr>
<tr>
<td>45mm red/charcoal bricks (for weights on the tarp)</td>
<td></td>
<td></td>
<td>$4.32</td>
<td>$4.32</td>
</tr>
<tr>
<td>1/2&quot;x5' S40 PVC Pipe (2)</td>
<td></td>
<td></td>
<td>$3.34</td>
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<tr>
<td>1/2&quot; ELL SCH 40 (5)</td>
<td></td>
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<td>$1.20</td>
<td>$1.20</td>
</tr>
<tr>
<td>TF 10&quot; Economy Hacksaw</td>
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<td></td>
<td>$4.95</td>
<td>$4.95</td>
</tr>
<tr>
<td>10&quot; /25T Bi-Metal blade (2)</td>
<td></td>
<td></td>
<td>$2.98</td>
<td>$2.98</td>
</tr>
<tr>
<td>kobalt stainless steel scissors</td>
<td></td>
<td></td>
<td>$4.98</td>
<td>$4.98</td>
</tr>
<tr>
<td>wire ties assorted sizes</td>
<td></td>
<td></td>
<td>$5.28</td>
<td>$5.28</td>
</tr>
<tr>
<td>duck tape (black)</td>
<td></td>
<td></td>
<td>$5.27</td>
<td>$5.27</td>
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<tr>
<td>emergency radar reflector (DAV 151)</td>
<td><a href="http://www.shipstore.com/SSHTML/DAV151.html">www.shipstore.com/SSHTML/DAV151.html</a></td>
<td>$23.70</td>
<td>$17.00</td>
<td>$40.70</td>
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<tr>
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<td>$375.00</td>
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<td>fish scale (qty 2)</td>
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<td>gas-bp wilmington pike</td>
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<td>2GB SD card - command module camera</td>
<td>Best Buy</td>
<td>$99.99</td>
<td></td>
<td>$99.99</td>
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<tr>
<td>79° and 88° neon orange and white parachutes</td>
<td></td>
<td></td>
<td>$9.95</td>
<td>$9.95</td>
</tr>
<tr>
<td>9V lithium ion batteries (3 tanks=3*36.75)</td>
<td></td>
<td></td>
<td>$110.25</td>
<td>$110.25</td>
</tr>
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<td>detailed state maps - oh, ind, ken, mich, wv, penn (rand mcnally)</td>
<td><a href="http://www.randmcnally.com">http://www.randmcnally.com</a></td>
<td>$133.19</td>
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<tr>
<td>microsoft streets and trips 2007</td>
<td><a href="http://www.circuitcity.com">www.circuitcity.com</a></td>
<td>$129.99</td>
<td>$8.08</td>
<td>$138.07</td>
</tr>
<tr>
<td>Garmin GPS chips - 29Hs and 15L-W</td>
<td><a href="http://www.startime-intl.com">www.startime-intl.com</a></td>
<td>$250.67</td>
<td>$7.01</td>
<td>$267.68</td>
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<tr>
<td>3x 244 cu. ft. tanks Helium (3 tanks=3*36.75)</td>
<td>WSU - through Greg Wilt</td>
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<td>$110.25</td>
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<tr>
<td>2way radios &amp; 2006 atlas</td>
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<td>$47.92</td>
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</table>

$1,866.40
The expenses specific to the SMP composite project are listed below.

<table>
<thead>
<tr>
<th>Product</th>
<th>Vendor</th>
<th>Price</th>
<th>Shipping</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>great stuff (window and door) for casting idea</td>
<td>lowes</td>
<td>$6.75</td>
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<td>plastic buckets (1QT and 2.5 QT) to use as molds for casting idea</td>
<td>lowes</td>
<td>$2.16</td>
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<tr>
<td>thermax sheathing 1/2’x4’x8’</td>
<td>lowes</td>
<td>$18.34</td>
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<tr>
<td>thermax sheathing 3/4’x4’x8’</td>
<td>lowes</td>
<td>$20.96</td>
<td>$13.50</td>
<td>$34.46</td>
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<tr>
<td>minco heaters - prototype design pack</td>
<td>Minco [<a href="http://www.minco.com">www.minco.com</a>]</td>
<td>$189.00</td>
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<tr>
<td>thermax sheathing (1/2’ and 3/4”)</td>
<td>Stock Building supply [807/337-9444]</td>
<td>$43.06</td>
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<tr>
<td>utility knife &amp; steel square</td>
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<tr>
<td>epoxy adhesive, latex gloves, plastic putty knife</td>
<td>Home depot</td>
<td>$11.77</td>
<td>$11.77</td>
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<tr>
<td>minco temperature controller candidates</td>
<td>[<a href="http://www.minco.com">www.minco.com</a>]</td>
<td>$96.00</td>
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<tr>
<td>makita 18V lithium ion batteries and charger</td>
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<td>$298.00</td>
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<tr>
<td>minco, controller ct 325, fep heater, rtd thermocouple</td>
<td>[<a href="http://www.minco.com">www.minco.com</a>]</td>
<td>$310.95</td>
<td>$310.95</td>
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<tr>
<td>McMaster</td>
<td>[<a href="http://www.mcmaster.com">www.mcmaster.com</a>]</td>
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<td>$68.83</td>
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<td>loweS - parts: 1 bracket payload box, screws</td>
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<tr>
<td>minco - candidate heaters - rectangle</td>
<td>[<a href="http://www.minco.com">www.minco.com</a>]</td>
<td>$207.80</td>
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<tr>
<td>home depot - nylon nuts and bolts</td>
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<tr>
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<td>Tiger direct</td>
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<td>timer relays for timer circuit</td>
<td>Hobbytron.com</td>
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<tr>
<td>quickshot, 16g thread, 12g thread co2</td>
<td>[<a href="http://www.performancebike.com">www.performancebike.com</a>]</td>
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<td>abstract</td>
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<td>characterization cameras - fuji film fine pix a500</td>
<td>Circuit city</td>
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<td>brass adjustable vacuum/pressure relief valve</td>
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<td>nylon bolts and nuts 5/8”</td>
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<td>$4.00</td>
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<tr>
<td>ultilflate plus co2 inflation system</td>
<td>[<a href="http://www.performancebike.com">www.performancebike.com</a>]</td>
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<td>$31.97</td>
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<td>16g threaded, 12g threaded</td>
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<td>servo arms for pressure trigger</td>
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<td>$15.98</td>
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<td>$18.03</td>
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<td>solid state relays for heating controllers</td>
<td>Digkey Corp</td>
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<td>epoxy tiga md 48, dow rtv 736</td>
<td>McMaster Carr</td>
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<td>quick change adapter - 12g</td>
<td>Tippman parts</td>
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<td>Budget Robotics</td>
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<td>$4.05</td>
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<td>hk5431r6.5l12f</td>
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<td>hk5288.hk5397.hk5390.hk5168, thermistor</td>
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<td>tc401115a - type t thermocouples, kapton film</td>
<td>[<a href="http://www.minco.com">www.minco.com</a>]</td>
<td>$232.30</td>
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<td>usb based 8 channel “usb-temp” - by measurement computing</td>
<td>Adept Science</td>
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<td>[<a href="http://www.korit.com">www.korit.com</a>]</td>
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<td>onset type t hobo temperatures data logger and type t thermocouple</td>
<td>Adept Computer Corp</td>
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</table>

$4,055.30