Payload Evolution and Engineering: A Reevaluation of the Strength, Efficiency, and Design of High-Altitude Balloon Payloads

Alondra Hauser, Nathan Leusink, Robert Clayton, Ryan Klimek

Pikes Peak Community College

Faculty Advisor: Rob Gilchrist

Rob.Gilchrist@ppcc.edu

April 9th, 2018

Abstract

For almost three decades, the Colorado Space Grant Consortium has sponsored student projects to launch high-altitude weather balloon payloads for short duration launches. Over the years, customs have developed for balloon payload designs and technology. In balloon launches, surviving severe near-space conditions, managing load weight, and maintaining efficient use of space and structure often differentiate between failed and successful missions. After reexamining payload norms, it is evident that wasted space, excessive circuitry, inefficient heating mechanisms, and faulty or vulnerable materials and shapes have come to dominate payload design. While these conditions may not always lead to mission failure, the loss of project capability is indisputable, making reconsideration worthwhile. To accomplish the goal of maximizing efficiency and introducing more effective technologies, this project details the process of breaking down payload design into its constituent components to reengineer those features. The final design will be verified and enhanced through extensive flight simulating conditions on ground level, and it will be launched for a comprehensive proof-of-concept test. By challenging typical approaches to balloon payloads such as the cubical shape, extensive heating apparatuses, and large circuit and sensor packages, this new design will provide new opportunities and insight for future balloon payloads. Ultimately, the result is expected to be a highly adaptable design that minimizes weight while maximizing volume, strength, and heat efficiency, providing various accessible options for future balloon launches.
1. Introduction

Challenging old ideas and methods is one of the only ways to progress and development better solutions in the field of technology. Reevaluating the norms and reengineering balloon payload systems has been the mission of Team Phoenix from day one. This project has successfully developed a new and thoughtful method of atmospheric analysis. By focusing on improving the circuitry, heating, and structure, a payload design that is sustainable, accessible has been developed. For the circuit package, the typical Arduino Redboard interface used to gather atmospheric data has been replaced by a more powerful, lightweight, and versatile Teensy circuit board. The heating apparatus was substantially improved by limiting the number of heaters and batteries needed for the mission and refining the payload insulation. Different structures for the payload were carefully tested to determine the shape that provides the highest strength and volume at the lowest mass. The data collected from this research will benefit other researchers performing high-altitude, short duration balloon launches. This report provides the process and information gathered in the process of rethinking and redeveloping basic balloon payloads, which will enable others to replicate the process in order to complete a successful launch.

2. Technical Research Results

2.1 Circuitry Redesign

2.1.1 The Teensy Circuit Board

To create a light and efficient payload, the circuitry has been completely redesigned. The first step was to create and program the circuitry on a familiar interface, which was the popular Arduino Redboard with 5-volt sensors. This sensor package included an internal and external temperature sensor, a humidity sensor, and a pressure sensor (Figure 1). Once this system was successfully programmed and capable of collecting data, the setup was then systematically transferred to a smaller, more powerful circuit board. The board that was chosen was the Teensy circuit board, created by the electronics developer PJRC [2]. The advantages of the new board are numerous, including improved processing power, additional digital pins for running more sensors, and substantially lower weight and size than the Redboard. More specifically, the board weighs only 5 grams, includes over 30 pins, and a contains a processor that can run a 32-bit adjustable Computer Operating System. By comparison, the 18-gram Arduino Redboard has only 14 pins, and a lower, non-adjustable processing speed. Perhaps the most effective utility of this board is the Micro-SD card port built into the back of the board. While this utility is incredibly beneficial, adjusting the sensor package code to accommodate that SD card port can be problematic (see section 2.1.3). Another advantage of the Teensy board is that it does not require a barrel adapter to power it independently of a computer. Users can operate this board with a USB cable or hard wiring power through the voltage-in port, as long as the voltage is limited to 6-volts or less. In the following section, the testing the board has been organized into three distinct stages: the testing of sensor readings, the programming and usage of SD card port, and the construction of a power adapter.

2.1.2 Sensor Integration

The first stage of testing involved transferring the four working sensors from the Redboard to the Teensy interface. Initial test runs for the Teensy were powered for the regular 5-volt sensor package. This sensor package had been confirmed to work on an Arduino Redboard, but integrating this package into the Teensy...
was a challenge. Initially, the sensor readings were inaccurate and fluctuated greatly. Several different explanations were proposed in an attempt to fix the problem. First, the wiring connections were adjusted to ensure that readings were not fluctuating due to poor connections. Second, sensors were replaced to ensure that the sensors were not the problem. Eventually, it was determined that the problem was caused by the initial wiring. In an effort to reduce weight, the heating apparatus was connected to the same circuit. This apparatus included a 4Ω resistor heater. Once this heater was removed, the readings stopped fluctuating, indicating that the heater was drawing too much current and distorting the sensor readings.

![Figure 2: Teensy (Left) Sensor package (Right)](image)

Despite this fix, the sensor readings were still not the expected results. It was soon discovered that there are two types of Teensy boards with many of the same capabilities discussed above. These models are the Teensy version 3.6, and the Teensy version 3.5. Because it has more capabilities, the Teensy version 3.6 was used initially. However, the 3.6 is not five-volt tolerant. This proved to be a quite problematic since the sensors were being run off of 5-volts. Before long, the board’s central processing unit burnt out because the board was not made to process using 5-volts. After reading about the different voltage tolerances of the Teensy boards, the obvious solution was to obtain and test the Teensy 3.5, which is 5-volt tolerant. After correcting the problem with the board, the sensor package testing continued. While unusual sensor readings were initially obtained, it was determined the input voltage of 3.3-volts was altering the sensor readings. The coding in the initial program was designed for 5-volt operation. After manipulating the algorithm that translated the sensor outputs to temperature, humidity, and pressure readings, the sensors accurately recorded the data.

### 2.1.3 Onboard SD Card Port

The second step of Teensy testing revolved around the SD card reader. On conventional payloads, an external SD card reader called the OpenLog is used. This device records outputs from the circuit board and sensors onto the SD Card. This allows data to be collected independently of a computer. The onboard SD card reader on the Teensy was able to replace this device and substantially decrease weight and increase efficiency. After extensive testing, the onboard SD card proved to be capable of performing the same job as the OpenLog. The primary challenge in incorporating this reader was selecting the correct coding libraries to reference and adjusting existing code to accommodate an entirely new SD card interface. Unfortunately, the onboard SD port lacks one of the capabilities of the OpenLog. Unlike the Teensy board, the OpenLog automatically opens a new file when it starts receiving new data from the circuit board. In order to function, the Teensy requires the code to create a new file in the set-up loop when new data is received. Then, the file must be opened before sensor readings commence and closed after the loop is complete. Using this method, data was successfully recorded for the duration of the payload mission.

### 2.1.4 Voltage Regulator

The last step in testing the Teensy concerned the power source. Many balloon payloads in the past have severely over-estimated the amount of power needed for the mission. This excess power introduces unneeded weight and reduces the efficiency of the mission. It is not uncommon for payloads to include as many as five 9-volt batteries. After testing different battery capabilities, only one 9-volt battery was needed for this mission. The voltage drop through the circuit was controlled using a 5-volt voltage regulator. This supplied the proper voltage to the Teensy circuit board. This battery proved to be more than enough to power the circuit board and sensor package. While this single battery was capable of also powering the heater, the heater drew too much power, causing the sensor readings to fluctuate drastically (see section 2.1.1). In the end, the Teensy circuit board required much less power than many payloads and it successfully recorded data for the duration of the flight.
2.1.5 Improvements for Future

During the mission, the only problem with the operation of the Teensy board and sensor package was in the applied voltage. Because the sensors were powered with 3.3-volts rather than 5 volts, the code was reconfigured to make the readings match the five-volt readings at standard room temperature, humidity, and pressure. However, the sensors were designed to give outputs between 0 and 5 volts rather than 0 and 3.3 volts. As a result, the sensors lost part of their range in the extreme high-altitude conditions. For instance, when 5-volts are applied to the sensors, the temperature sensors are capable of recording temperatures as low as -70 degrees Fahrenheit, the anticipated minimum temperature during flight. Because only 3.3-volts were applied, however, the minimum reading of the temperature sensor was -20 degrees Fahrenheit. To solve this problem in the future, it is necessary to either apply 5-volts directly from the voltage-battery-port on the board or use 3.3-volt sensors.

2.2 Structure Redesign

2.2.1 Physical Shape Design

The final redesign of the payload altered the shape itself. Rather than taking a conventional approach with a box shaped payload, different shapes were tested to find out which was the strongest and most durable. After researching possible shapes, it was decided to test a square pyramid, sphere, dome, cube, and tetrahedron. These shapes needed to be strong, light, and have enough volume to house the insulation and circuity. An experiment was designed to test all of these factors. Plastic models of these shapes were obtained, and the weight and the volume of each shape was recorded. After researching pressure devices, a device for spring testing was used. This device compressed two sides of an object and used a spring to register the maximum force exerted. The crushing force, weight, and volume were then compounded in a triple ratio. Because the mass was placed in the denominator and the strength and volume were placed in the numerator, the shape with the highest overall ratio had the best balance of strength, volume, and mass. In other words, the triple ratio identified the most efficient design by considering the strength, mass, and volume. This was accomplished by multiplying all of the values that would ideally be very large and dividing by the values that would ideally be very small. Weight was squared in order to give it double importance in the ratio. This data revealed that the most efficient shape was the sphere. The results of this test are summarized in Table 1.

Table 1. Data from Crush Test

<table>
<thead>
<tr>
<th>3D geometric shape</th>
<th>Material</th>
<th>Dimensions</th>
<th>Volume meters cm^-3</th>
<th>Surface area cm^-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Pyramid</td>
<td>Clear</td>
<td>h=5.7cm, w=5.31cm</td>
<td>53.57</td>
<td>94.97</td>
</tr>
<tr>
<td>Sphere</td>
<td>Clear</td>
<td>r=2.78cm</td>
<td>90</td>
<td>97.12</td>
</tr>
<tr>
<td>Cube</td>
<td>Clear</td>
<td>w=5.56cm</td>
<td>171.51</td>
<td>185.23</td>
</tr>
<tr>
<td>Tetrahedron</td>
<td>Clear</td>
<td>a=6.35cm</td>
<td>30.18</td>
<td>69.84</td>
</tr>
<tr>
<td>Dome</td>
<td>Clear</td>
<td>r=2.78cm</td>
<td>45</td>
<td>72.84</td>
</tr>
</tbody>
</table>

Weight, Crushing Force, Mass per unit volume, Crushing force to mass ratio, Force/volume/mass \(^2\)

<table>
<thead>
<tr>
<th>Weight g</th>
<th>Crushing Force N</th>
<th>Mass per unit volume</th>
<th>Crushing force to mass ratio</th>
<th>Force/volume/mass (^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.6</td>
<td>1467.91</td>
<td>0.320542094</td>
<td>8.403977272</td>
<td>253.8668550</td>
</tr>
<tr>
<td>15.7</td>
<td>1423.43</td>
<td>0.174444444</td>
<td>90.66433121</td>
<td>519.731835</td>
</tr>
<tr>
<td>38.8</td>
<td>1556.88</td>
<td>0.179581366</td>
<td>58.54065195</td>
<td>281.4771555</td>
</tr>
<tr>
<td>8.7</td>
<td>622.75</td>
<td>0.288270378</td>
<td>71.58045977</td>
<td>248.3101467</td>
</tr>
<tr>
<td>12.26</td>
<td>1467.91</td>
<td>0.272444444</td>
<td>119.7316476</td>
<td>439.4717898</td>
</tr>
</tbody>
</table>

2.2.2 Material and Insulation

After integrating the teensy into the payload, the next phase of research involved heat retention. Styrofoam was introduced as the primary building material because it acts as an efficient and low weight insulator. However, it was still a challenge to keep the batteries alive long enough to analyze consistent data during freezer tests. After many failed tests, it was concluded that the heat lost proved to be a result of poor insulation. The first solution involved the use of
emergency blankets. The space blanket insulation can be seen inside the sphere in Figure 4.

![Figure 4. Heater with Insulation and Space Blanket](image)

While this insulation did retain heat, it did not stop the leakage all together. The second design that was implemented used of Armacell Insulation [1]. This insulation is used on household pipes to keep them from freezing in the winter. The interior of the payload was coated in this spongy material. The final source of heat loss originated from the flight tube, which attaches the payload to the high-altitude balloon. Since this tube was directly exposed to the external environment, it proved to be a major source of heat loss. The solution to this issue also involved the use of the Armacell Insulation [1]. Wrapping the flight tube in this material provided two advantages. First, this layer stopped the majority of heat loss through the flight tube. Second, it provided an excellent mounting area for the internal sensors and the Teensy circuit board.

### 2.2.3 Launch Requirement Redesign

Colorado Space Grant requires the use of a flight tube and two washers to securely attach the payload to the weather balloon. However, these components comprise a large portion of the mass of the payload. After researching alternatives, each new alternative was tested. The final iteration of the payload included a much smaller washer. This washer weighed nine times less than its predecessor. Also, an improved flight tube was used that took advantage of lightweight Polybutylene Pipe. This proved to be just as strong as the original flight tube.

### 3.1 Heater Redesign

Another component in effort to improve payload efficiency was the redesign of the heating system. Due to extreme temperatures as low as -70 degrees Fahrenheit, the heater is a crucial part of the internal system. Multiple new heating systems were constructed to determine the one that would provide the necessary heat at the lowest weight. The heating apparatus of most high-altitude balloon payloads consist of three 4Ω resistors powered by three 9-volt batteries. Even with lightweight batteries, this weighs almost 80 grams and provides an excessive amount of heat to the payload. To avoid this inefficiency, a new system was developed that used only two AAA batteries and one 4Ω resistor heater. This setup weighed just 26 grams and lasted for the duration of the mission. During the mission, the payload’s internal temperature dropped to 5 degrees Fahrenheit, while the outside temperature was -70 degrees Fahrenheit. Some of the other systems that were tested and proved to be insufficient due low energy flow used only one AA battery or two 3 Volt coin batteries. Instrumental to the success of this heating system was the insulation that was developed for the flight (see section 2.2.2).

![Figure 5. Payload Heater](image)

### 3.1.1 Use of Cold Weather Batteries

While the use of cold resistant batteries and insulation is currently used for some flights, there are new and more efficient methods for maintaining internal temperature. Both the 9 Volt battery and the two AAA batteries can reach temperatures as low as -40 degrees Fahrenheit before losing power. Furthermore, the sensors and Teensy circuit board are capable of surviving well beyond the -40 degree Fahrenheit threshold. This was proved using a –70 degree Fahrenheit freezer. After two hours in this extreme temperature, the batteries died because they were not properly insulated and heated. This caused
the circuit to power off. However, when new batteries were plugged into the circuit, it powered on again and continued collecting data. This experiment proved that the circuit board is even more tolerant of low temperatures than the batteries are. Using the right insulation in the next freezer test, the power to the heater lasted a little over two and a half hours. Even though the predicted flight time lasted just over three hours, during the flight, the payload would not experience temperatures as low as -70 degrees Fahrenheit for the duration of the flight. Thus, the freezer test proved that the heater that used two AAA batteries would be sufficient. During the flight, the heater lasted long enough to protect the Teensy board. After review of the internal temperature readings, the minimum temperature inside the payload was 5 degrees Fahrenheit, well above the minimum temperature for the batteries. This design substantially improved the efficiency of the heating system and drastically reduced the final weight of the payload.

3.1.2 Payload Insulation for Heat Loss Reduction

The final portion of the heater redesign involved insulation. Even though it was proven that the heater could provide consistent heat for the duration of the flight, much of that heat was lost due to poor insulation. The first solution involved the use of an aluminum and substrate emergency blanket, which reflects 70% of internal heat. While this method did improve the retention of heat, more insulation was still needed. The second design that was researched implemented the use of a Polybutylene tubing insulation. This insulated the Polybutylene flight tube that attached the payload to the flight string. The insulation was used to prevent the loss of heat by conduction through the tube. This insulation is commonly used on household pipes to keep them from freezing in the winter. This made the payload almost entirely insulated from the outside environment. Using these layers of insulation as well as the cold-resistant batteries allowed the entire payload to run at full capacity with a much lower weight. If a higher temperature is needed for a larger payload, then more than one resistor could be used just as easily.

![Figure 6. Flight Tube with Insulation Cover](image)

4. Conclusion

Ultimately, Team Phoenix’s goals revolved around efficiency. Instead of following standard procedures, common systems were redesigned and a new, more efficient and adaptable payload was developed. This redevelopment included the circuit package, the payload structure, and the heating subsystem. Before this research, the same components occupied a box that weighed over 400 grams. After reengineering each of the main features of the payload, I weighed just under 150 grams. Aside from the weight, the overall structure is stronger and the circuit package has more potential to expand into a plethora of other applications. All of this lead to a much more efficient payload, granting future payloads increased opportunities from the extra weight and space in which to personalize their projects.

5. References

[1] https://www.armacell.us/home/
In Flight Data

Payload Weight Summary

<table>
<thead>
<tr>
<th>Part</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>9V Battery</td>
<td>34 grams</td>
</tr>
<tr>
<td>Circuitry</td>
<td>18 grams</td>
</tr>
<tr>
<td>Sphere</td>
<td>25 grams</td>
</tr>
<tr>
<td>Insulation</td>
<td>12 grams</td>
</tr>
<tr>
<td>Tube</td>
<td>17 grams</td>
</tr>
<tr>
<td>Washers</td>
<td>2 grams</td>
</tr>
<tr>
<td>Heat Package</td>
<td>26 grams</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>134 grams</strong></td>
</tr>
</tbody>
</table>

Sensor Package Flight Data

- Internal Temp (°F)
- External Temp (°F)
- Percent Humidity
- Pressure (psi)