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Bringing the Heat to 100,000 Feet: The Capacity of HotHands to Facilitate High-Altitude Research

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Abstract

Weight is a major limiting design factor for in-flight experiments. Additionally, when sending electronics to high altitude, temperature must be kept high enough to keep equipment functioning. The current recommendations for heating during Demosat flights include a weight-heavy battery powered ceramic resistor. We tested if a small, lightweight, battery-free heating source such as HotHands hand warmers were able to keep electronics warm enough to function during flight. We successfully collected 3:17 hrs of data during flight, indicating that future DemoSat payloads can use HotHands as a heating source. This will allow future Demosat payloads to fly heavier experimental equipment to further advance high-altitude science.

The exothermic reaction of HotHands is oxygen dependent and therefore has limited heat production in the oxygen-poor upper atmosphere. This paper provides recommendations for insulating the payload and providing secondary containment with desiccation to protect electronic instrumentation from condensation produced during flight.

We used microbes to determine if the proposed HotHands heating system is sufficient for biological research at high-altitude. We used Winograsky columns to determine if exposure to high atmospheric environments had an effect on microbial communities in soil. The study of microbial consortiums at high altitudes will be critical in the support of long-term space missions and has potential applications in the terraforming of Mars. Further, we tested soil microbial communities sampled from two altitudes (14,000ft vs 5,300ft) to see if niche altitude affects tolerance during high-altitude flights. Microbial growth was evaluated in Winogradsky columns after flight.

Introduction

The electronics used for DemoSat missions are rated to function normally above -40°C/-40°F. Payloads generally reach an altitude of 90,000ft, and can be exposed to temperatures around -40°C/-40F to 60°C/-76°F. While most arduino boards have a minimum operating temperature of -40°C/-40°F, the recommended minimum operating temperature for an arduino is -25°C/-13°F to avoid damage to sensors and batteries. Currently, a battery powered ceramic resistor is used to preserve heat.

Weight and space are the major limiting design factors when designing experiments to fly on high-altitude payloads. Additionally, when sending electronics to high altitude, temperature must be kept high enough to keep equipment and experiments functioning. The current recommendations for heating during Demosat flights include a weight-heavy battery powered ceramic resistor. We tested if a small, lightweight, battery-free heating source such as HotHands hand warmers were able to keep electronics warm enough to function during flight. Our DemoSat payload measured 3:17 hrs of data, the successful use of HotHands in this DemoSat test flight provides data allowing future payloads to confidently use alternative heating technology. The team hopes this will enable future payloads to fly heavier experimental equipment to further advance high-altitude science.

HotHands generate heat in an oxygen dependent manner. HotHands relies on an exothermic iron reduction reaction to produce heat. Each pack contains iron powder (Fe_2) which is reduced upon reacting with oxygen in the atmosphere (O_2). It is then further oxidized by oxygen and water into rust (Fig. 1).

$$Fe(II) + O_2 \rightarrow Fe(III) + O_2^-$$
$$Fe(II) + O_2^- + 2H^+ \rightarrow Fe(III) + H_2O_2$$

Figure 1. Chemical equation for HotHands (King et al., 1995).

DemoSat payloads are exposed to a high atmospheric, anoxic environment for up to several hours. This presented a concern about the ability of the hand warmers to provide heat when one of reactants was limited. This study determined the internal payload temperature when using hand warmers during flight.

In addition to keeping the electronic systems functioning in low temperature environments, payloads often require heat to enable viable biologic experiments. We used two soil microbial consortiums to determine if the proposed HotHands heating system is sufficient for biological research at high-altitude. We analyzed if exposure to high atmospheric environments had an effect on microbial communities in soil using Winogradsky columns. The study of microbial consortiums at high altitudes will be critical in the support of long-term space missions and has potential applications in the terraforming of Mars. Microbial communities were sampled from two altitudes (10,900ft vs 5,300ft) to see if niche altitude affects tolerance during high-altitude flights.

Materials and Methods

Pre-launch Testing

HotHands Vacuum Test

The DemoSat payload is predicted to reach a maximum altitude of 90,000-100,000ft, where minimal oxygen is available to allow for the progression of the exothermic HotHands reaction. To ensure the efficacy of this project, the team subjected the HotHands to a vacuum to simulate the lack of oxygen in the upper atmosphere. Heat production from the HotHands was monitored inside of a vacuum chamber for thirty minutes. The HotHands temperature inside of the vacuum chamber dropped 16°C while the control outside the chamber remained at roughly the same temperature, varying about 2°C. It's important to note that the pressure achieved in the vacuum was roughly equivalent to the altitude of 65,000ft not 100,000ft. This experiment indicated that the payload would need to be well insulated to prevent heat loss during anoxic conditions in the upper atmosphere (Fig. 2).

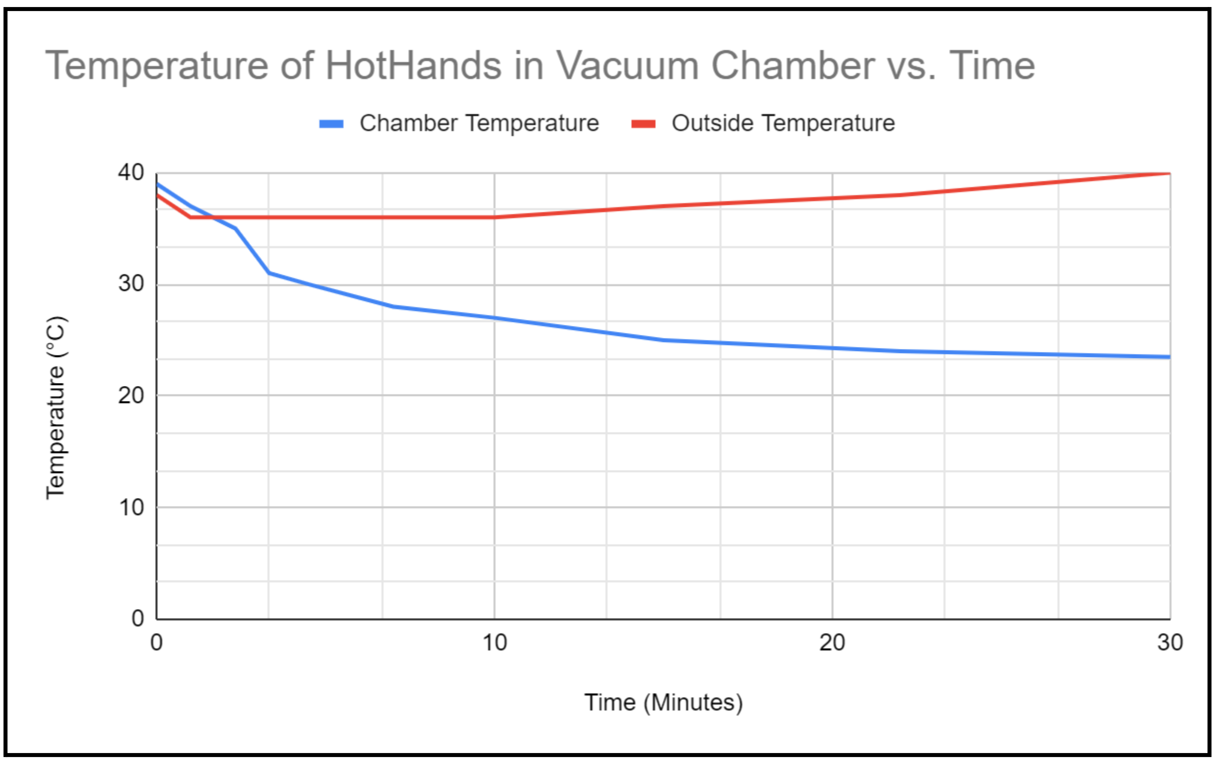

Figure 2. Temperature of HotHands within a vacuum chamber to test efficacy in low pressure/oxygen environments.

-80°C Freezer Test

The payload containing activated HotHands was also tested in the -80°C freezer. The internal temperature of the payload got down -3.8°C after 20 minutes. This data encouraged further testing during flight as the HotHands were able to generate a significant differential in internal and external temperature.

The -80°C freezer test also indicated there was a significant accumulation of condensation that created a short in the electronic system. This required re-organization of the payload to include isolation of the electronic components with an anhydrous calcium chloride desiccant wrapped in a coffee filter. A ziploc bag was used to contain the electronics and desiccant to further protect from condensation and prevent interference of the HotHands reaction.

Whip and Drop Testing

The whip and drop test were effective at measuring structural integrity of the payload. No structural damage was recorded. However there was an issue with the electronics intermittently recording data. Initial connectivity suspicions led the wires to be hot glued to the Arduino unit for security. When this did not solve the issue, it was concluded that condensation from the HotHands reaction may have collected within the electronics. The whip and drop test did indicate that water accumulated from the HotHands had to be isolated from the electronics.

Battery testing

The assembled electronics package went through a battery test before launch to ensure that the payload would have sufficient battery power for the entire flight. The result of the test showed that the payload would run and record data for a total of 28 hours and 9 minutes with a single 9V battery. This indicates that the 9V battery size was more than sufficient to power the payload.

Payload Structure and Design

Goals

The main objective of team HotHands was to come up with an alternative heat source for future DemoSat missions. The current guidelines for maintaining adequate heat levels during Demosat flights involve the use of a ceramic resistor and several heavy 9-volt batteries. While this approach has achieved optimum results for keeping electronics above the -40C required for them to function, it has come with sacrifices. The biggest sacrifice for maintaining the heat is the weight and size of the batteries. Our team's mission was to test how well the exothermic reaction from HotHands could be used at 100,000ft to maintain the required temperatures. One HotHand packet weighs 29.7g while one fully charged 9V battery weighs 47.82g. This drastic difference in weight will allow for more experiments to be included for future DemoSat missions.

Structure

The payload was designed with the intent of maintaining and trapping the heat produced by the HotHands without interfering with the electronics. Several steps were required for this goal to be achieved. The first step was to increase insulation, this was achieved by more than doubling the width of the outer foam core shell. Previous RRCC payloads have used an outer foam core shell with a width of 3mm. Our team vastly increased the insulative properties of the payload by increasing insulation width to 11.5mm. Additionally, insulative foam with a width of 11.5mm was hot glued to the inside of the payload structure. As we focused on insulating the payload, we hypothesized that the flight tube would be the most critical structure that could lose heat. To prevent thermal energy from being lost to the thin plastic tube, we wrapped it in insulating foam and hot glued it in place (Fig. 3).

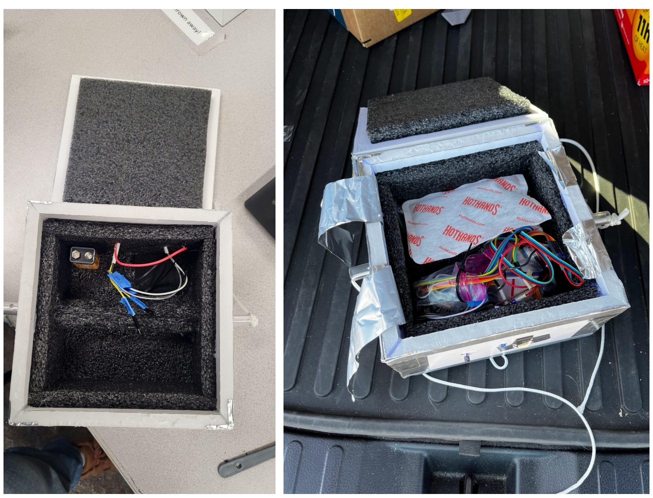

Figure 3. Payload box design with insulation and electronics.

The second step was to isolate the electronics from the HotHands reaction. In previous testing, it was concluded that the exothermic reaction achieved by Hothands was causing condensation to build up in the electronics. This caused the electronics to short and fail. To prevent this from happening again, the team isolated the electronics from the HotHands via a plastic bag with a desiccant in it. The plastic bag acted as a barrier to prevent any water vapor from seeping into the electronics, and the desiccant further aided in achieving this goal absorbing any left over water vapor.

Electrical

Our electronics were designed to give reliable data to determine if HotHands could act as a viable replacement for the heatsource currently used by DemoSat missions. Several variables were considered to determine the feasibility of this goal. Specifically, internal temperatures, external temperatures, barometric pressure, oxygen levels, elapsed time, and altitude were measured and analyzed. The electronics required to measure these variables include: microcontroller, temperature sensor, barometric pressure sensor, SD card, O2 sensor, 5v voltage regulator, LED, resistor, power switch, and a battery. See Table 1 for a list of major parts used.

The payload was designed to record internal and external temperature to assess the efficiency of the HotHands throughout the launch period. In addition, the payload carried an oxygen sensor to measure the relationship between oxygen and the exothermic reaction of the HotHands. Finally a sensor to record barometric pressure was added to show the correlation between barometric pressure and the HotHands ability to sustain a reaction. The major components for the payload electronics are listed in Table 1 below. The Arduino MKR Zero was selected as the main microcontroller for the payload as it offers a built in SD card slot and a more advanced processor with "low power" mode. The I2C oxygen sensor was selected as it provided low power consumption and an I2C interface to collect data from the sensor. The BMP180 barometric pressure sensor was also selected because of its I2C interface and low form factor. The TMP36 temperature sensors that were selected are standard SpaceGrant hardware and were easily readable using the analog in function on the arduino. See Figures 4 and 5 below for a picture of the complete payload wiring.

Table 1. List of primary electronic components.

Part Type	Part Name
Microcontroller	Arduino MKR Zero
Temperature Sensor	TMP36 Temperature Sensor
Barometric Pressure Sensor	BMP180 absolute barometric pressure sensor
SD Card	Micro Center 32GB Micro SDHC
O2 Sensor	DFRobot Gravity I2C Oxygen Sensor SKU:SEN0322
5v Voltage Regulator	AMS1117-5.0V SOT-223 5V Fixed Linear Voltage Regulator
LED	Blue LED

Resistor	220Ω Resistor
Power Switch	Electronic Toggle Switch
Battery	9V Battery

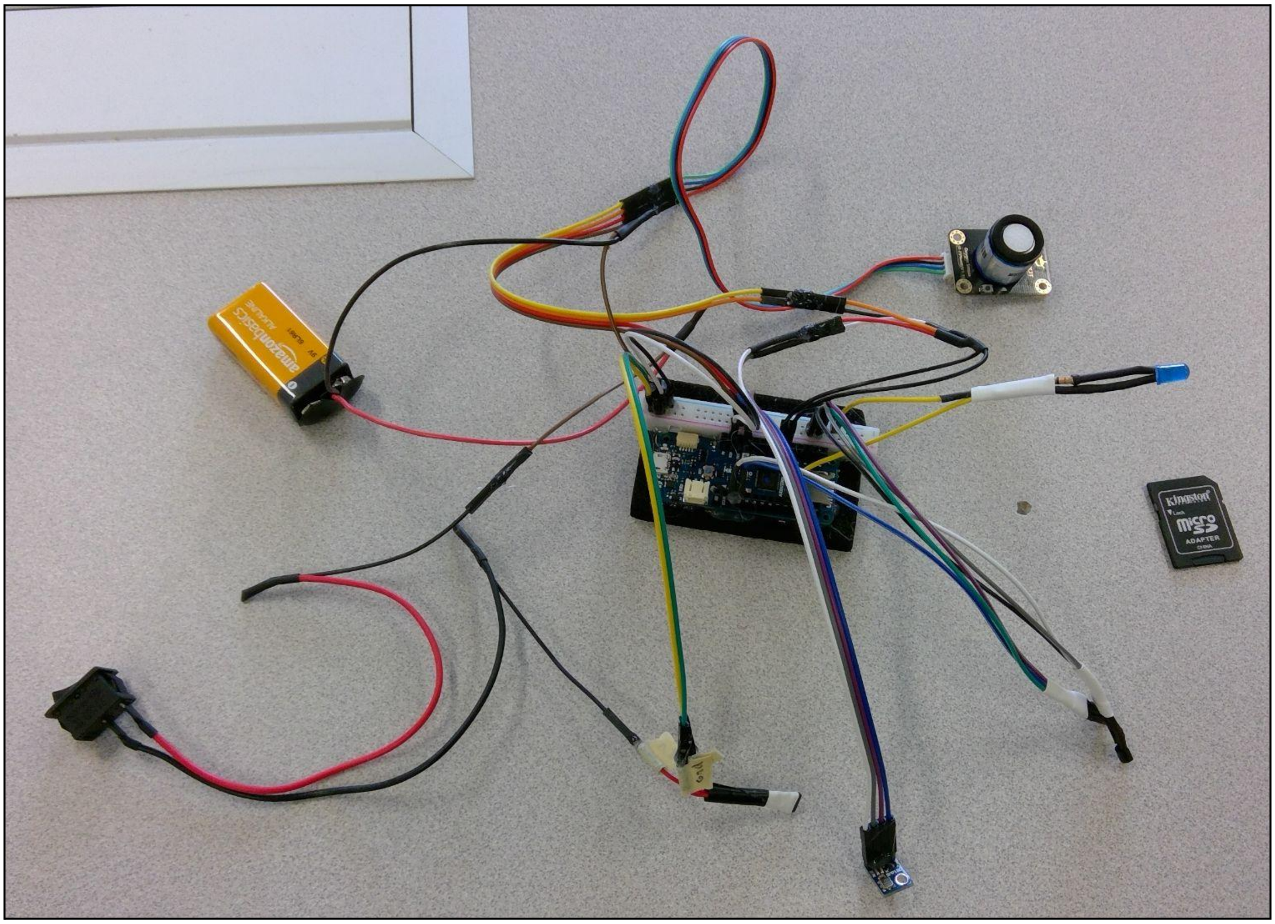

Figure 4. Finished wiring for electronics package. Including a power source, internal and external temperature sensor, a barometer and oxygen sensor. All sensor data was written to an SD card 12 times per minute.

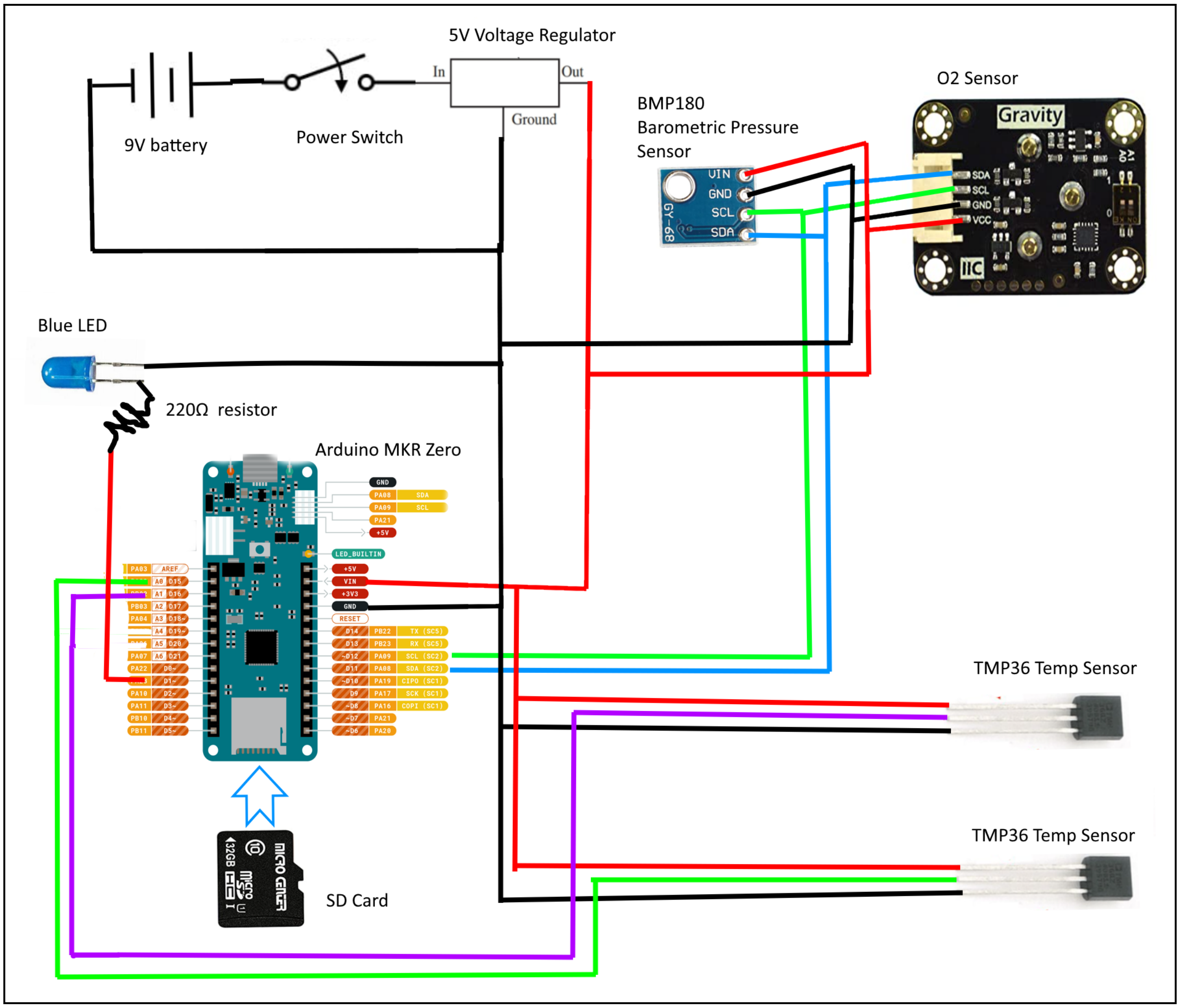

Figure 5. Circuit Wiring Diagram showing wiring for all components of the electronics package.

Winogradsky Columns

In many cases microbes can only grow within a community; the waste products of some microbes being critical nutrition for other microbes. Winogradsky columns are a lab technique used to analyze soil microbe communities. The design allows for a diverse array of microbes to grow, including aerobic, anaerobic, photosynthetic, and non-photosynthetic bacteria. The layers allow for the symbiotic growth of oxic, suboxic, and anoxic bacteria. Microbial stratification can be clearly seen in the glass Winogradsky columns due to varying color layers within the tube.

Soil samples were collected from two altitudes on March 28th, three days before launch. The first was from a field outside of Red Rocks Community College at an elevation of 5,800ft. The other was collected from the side of Guanella Pass in the Rocky Mountains at 10,900ft. Sterilized gloves and Whirl Pak bags were used to prevent microbial contamination. After recovery of the payload the launched samples as well as ground controls of non-flown soil were immediately processed intoWinogradsky Columns.

The soil from Guanella pass was frozen during collection and therefore had a higher water content than the samples collected from Red Rocks. To account for this discrepancy, the ratio of soil to water added to each column was adjusted to resemble similar consistency. The same amount of water (20g) was added to the Guanella soils (85g) and Red Rocks soils (45g).

Pond water was used for the columns for its ability to keep osmotic pressure consistent for microbes present in the soil. The water was sterilized via autoclave prior to integration to prevent microbial contamination. Additionally, nutrients were added to encourage microbial growth. Newspaper (0.1g) was thoroughly mixed into the mud as a carbon supplement. Carbon is needed to synthesize all molecules needed for life including DNA, proteins, and sugars. Boiled egg yolk (3.6g) was also added for a source of sulfur. Sulfur is necessary for the production of proteins and enzymes.

After the soil and nutrient mixture had been added to glass bottles, an additional centimeter of pond water was added. The assembled columns were placed in a window sill. The labels are intentionally placed facing away from the window to allow for maximum sunlight exposure. We hope to see diversity in the microbial communities including photosynthetic, non-photosynthetic, aerobic and anaerobic bacteria.

HotHands

Two HotHands hand warmers were used to warm the payload. They were placed on the opposite side of the payload to the electronics. This was to further prevent wires from becoming unplugged if the hand warmers were to move. Instead, they were played over the soil samples. The HotHands were stacked on top of each other. Since each packet contained wood fiber to trap moisture, this may have been favorable to keep water content preserved. Additionally, having the hand warmers in close proximity to the biological samples may have allowed for more microorganisms to survive.

Results

The payload successfully recorded data for 3:17 hrs throughout the flight and landing, with the exception of the oxygen sensor which broke upon landing. Internal temperature varied from 57°F to -2°F. The lowest temperature documented internally was -2°F while external temperature reached -35°F. Figure 6 presents data showing how the temperature inside and outside the payload vary over time.

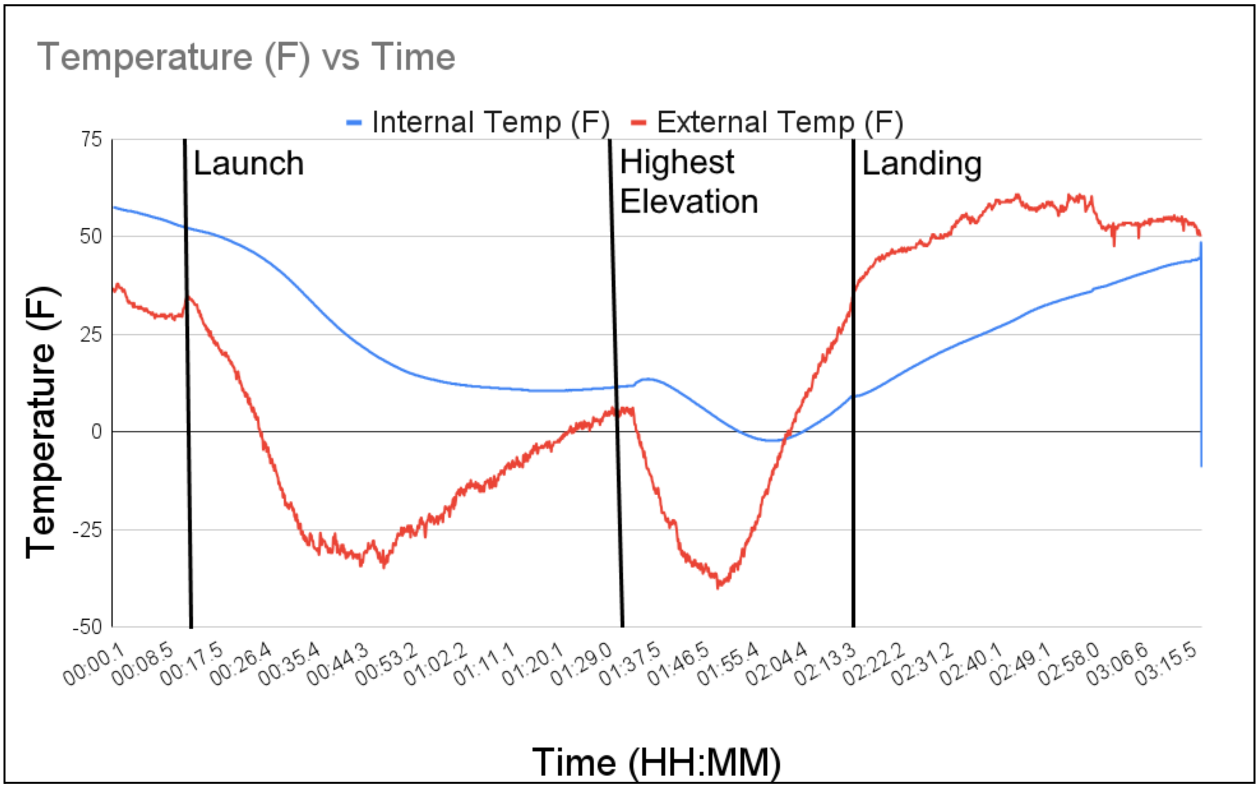

Figure 6. Internal and external temperature recorded throughout the duration of the high-altitude flight with time of launch, highest elevation, and landing indicated. Vertical bars indicate the launch, point of highest elevation and landing.

During testing prior to launch, the oxygen sensor recorded low oxygen concentration(~5%) when sealed with HotHands inside the payload. Figure 10 in the appendix shows the data from the oxygen sensor during testing with HotHands. During most of the ground test, the oxygen concentration was very low. When the payload was opened periodically, the oxygen concentration went up significantly, but as soon as the payload was closed again, the oxygen was quickly used up.

Figure 7 shows the relationship between oxygen concentration and internal temperature of the payload throughout the duration of launch. Although the oxygen concentration was low at high altitudes, decreasing the efficiency of the exothermic HotHands reaction, the internal temperature of the payload was sufficient to keep the electronics functional.

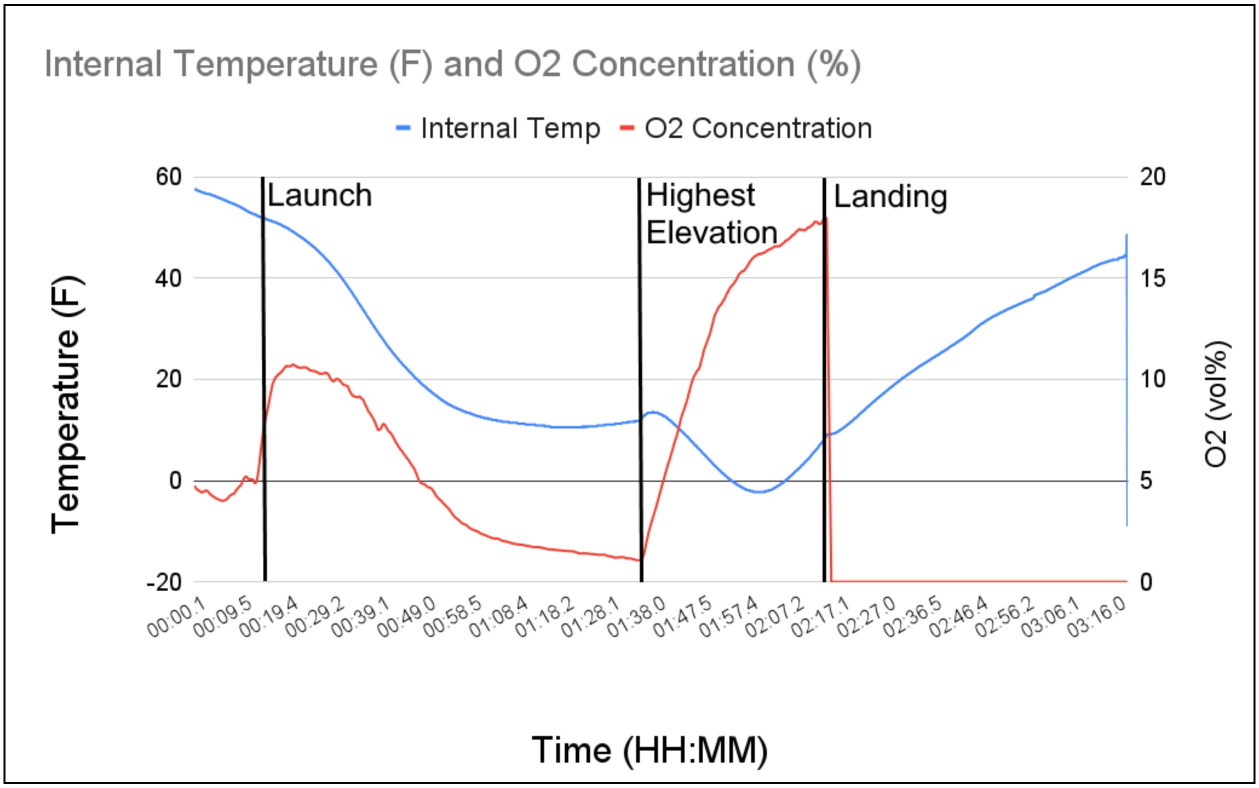

Figure 7. Internal temperature and oxygen volume percentage recorded throughout the duration of the flight with time of launch, highest elevation, and landing indicated by vertical bars. O2 levels are both dependent on altitude and the HotHands reaction. Previous testing showed dramatic reduction in O2 when the payload was closed with HotHands inside.

Figure 8 provides a comparison of external temperature vs altitude. This variation in temperature could affect internal payload temperatures.

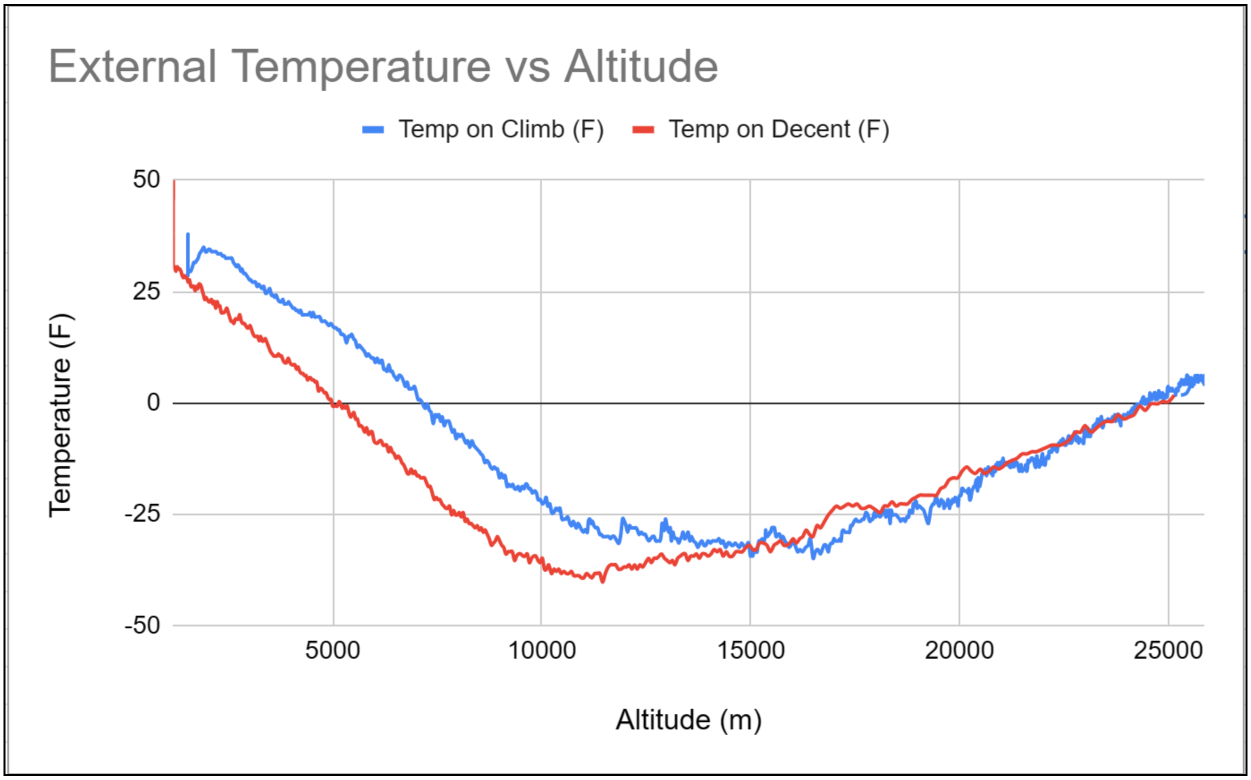

Figure 8. External Temperature plotted against altitude, showing that the two variables have a nonlinear relationship.

The Winogradsky columns have shown favorable progress in the development of symbiotic communities (Fig. 9). There is a visible difference between the flown and control samples from both altitudes. The Guanella Pass samples show a heavier contrast between the oxic liquid layers. The same can be said for the Red Rocks sample, though the difference is not as noticeable. It is worth noting the GP flown sample shows the most bacterial growth in the oxic liquid layer.

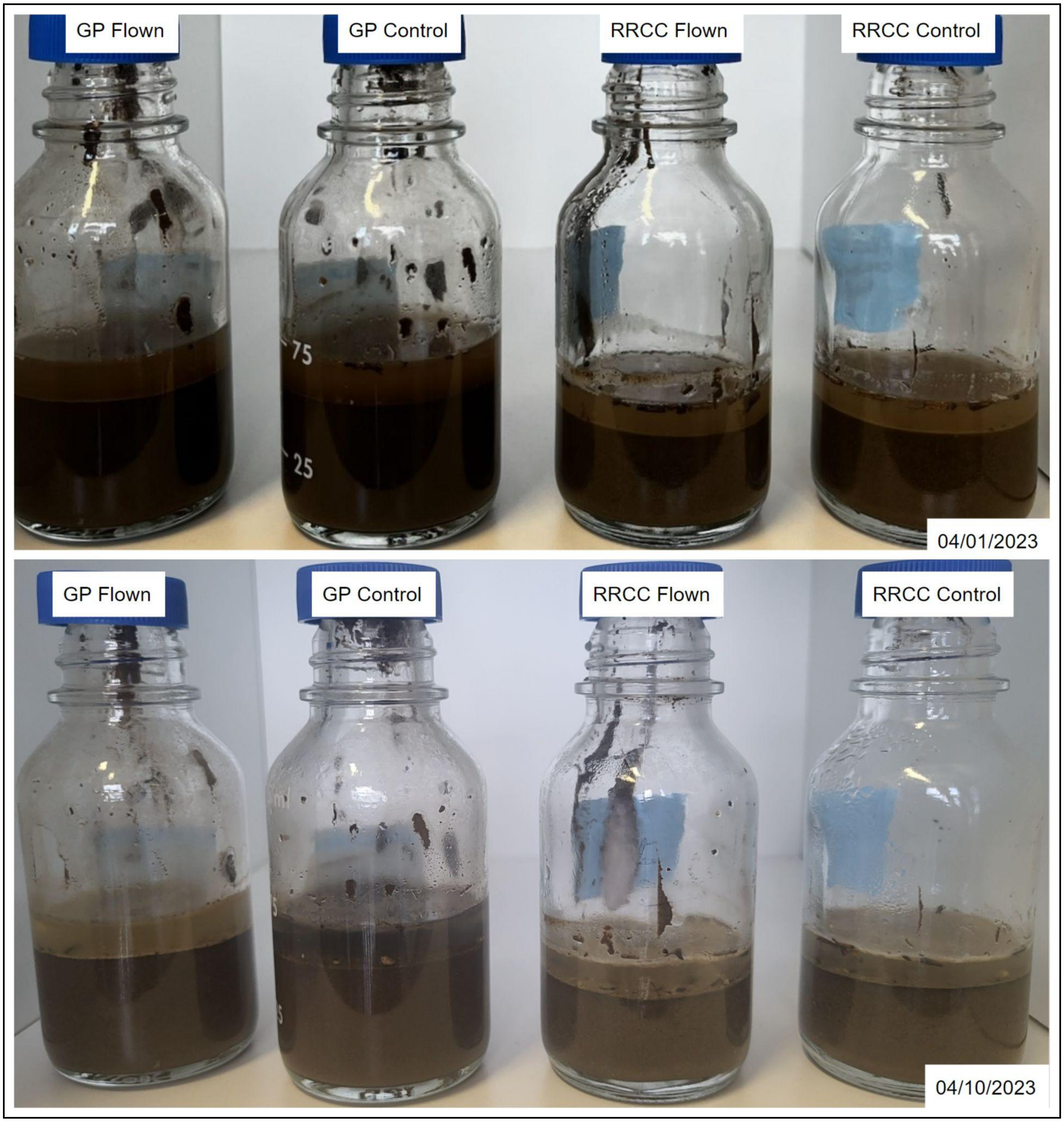

Figure 9. The top photographic panel is from day-0, the bottom photographic panel is from Day-10 Winogradsky Column Progress.

Discussion

The main objective of our team was incredibly successful! HotHands were more than capable of maintaining an appropriate temperature at which electronics could continue to function. Most sensors were able to collect data for the entire duration of the flight. External temperature reached as low as -40°F however the minimum internal temperature was -2°F (Fig. 6) . Surprisingly, it appears that the elevations between 30,000ft and 50,000ft are much colder than the upper parts of the flight (Fig. 8). This may potentially allow the HotHands to warm the payload when it needs it most during the early and late phases of the flight where the thicker atmosphere will allow for more heat generation.

Using HotHands as an alternative heat source for DemoSat missions comes with incredible benefits. The first major benefit is the reduction in weight. One fully charged D battery weighs 47.82g while one unused HotHand weighs 29.7g. This difference of 18.12g may seem negligible, but adds up to a substantial amount of weight reduction if multiple batteries are used to maintain heat. The weight limit for a single payload for a DemoSat mission is 800g. By replacing the current heat source with HotHands, future missions can have much more flexibility with the weight of their payload. The second major benefit is the amount of space created by using HotHands as a heat source. A HotHand packet and a D battery take up approximately the same amount of volume, but there are differences in how they can be stored. HotHand packets can conform and mold to be fit in multiple places in the payload. This allows for more inventive ways of creating usable space while still maintaining the appropriate heat. Beyond having superior packable capabilities, future missions can achieve the same heat that D batteries would, while using less material.

HotHands are designed to provide heat over the course of 11 hours and therefore are slow to begin heat up to operational temperature. The team activated the warmers approximately one hour and ten minutes before launch. This provided ample time for the HotHands to begin reacting and decreasing the O_2 concentration. The sensors, however, were not turned on until right before launch (Fig. 8). In future experiments, the team would begin data collection when the payload is sealed to track the oxygen depletion curve caused by the oxidation reaction.

Upon opening the payload after flight, all electronics seemed to be intact with the exception of the oxygen sensor. It appeared to have fallen off upon landing as it abruptly stopped recording at the same time altitude became constant.

The soil samples had low oxygen for the majority of launch due to both atmospheric and heating conditions. This experiment aimed to evaluate how soil microbes derived from different altitudes would react in high atmospheric conditions. However, any future payloads using HotHands looking to conduct biological experiments should be aware of the extended anoxic environment within the payload.

Secondary containment of electronics with desiccant is recommended. However, as the exothermic hot hands reaction requires water, the desiccant cannot be in proximity to the Hot Hands. Our team solved this issue using a plastic ziploc bag surrounding the electronics and desiccant. The HotHands were able to react effectively and no electronic sensors malfunctioned due to condensation accumulation during flight. To further reduce the weight and size of the desiccant, we recommend future missions to test using an activated emulsifier.

While the overall mission was a success. There were several things that went wrong with payload during the testing phase and flight. The biggest issue our team ran into was interference in our electronics from the reaction of the HotHands. The reaction required for HotHands to work involves heat and water. This caused a buildup of water vapor on the electronics causing them to malfunction. To negate this, our team separated the electronics in a plastic bag with a desiccant inside. The other issue that arose during flight thankfully happened at the end of the descent. The O2 sensor detached after the payload crashed into the ground. Future teams might want to hot glue these sensors down to prevent this from happening. The biggest recommendations for future missions if they use HotHands are to separate the hand warmers from the electronics, and to securely glue down electronics.

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Appendix

Figure 10 below shows the data from the oxygen test reference earlier in the paper. Figure 11 below shows the data of the internal and external temperatures of the payload during the freezer test.

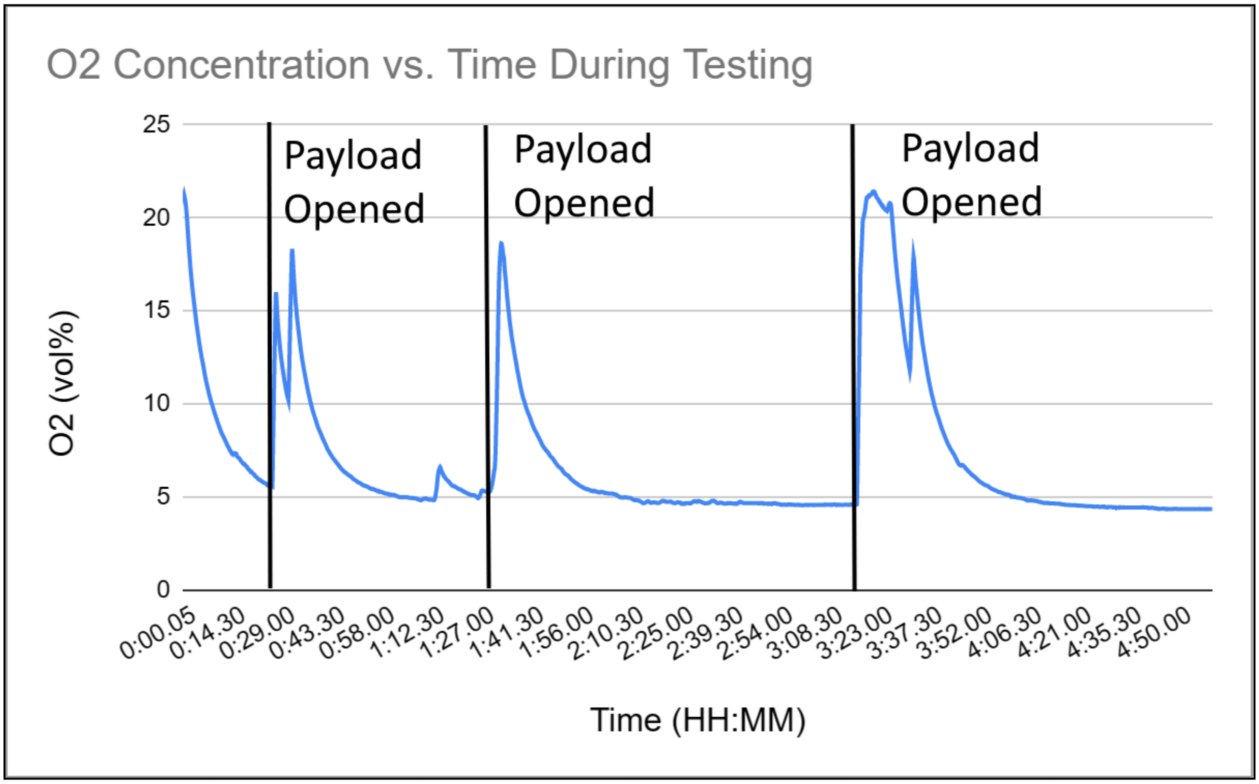

Figure 10. The Oxygen Concentration recorded during the testing of Hot Hands prior to launch. Vertical bars indicated points where the payload was opened and the oxygen concentration restored to atmospheric levels.

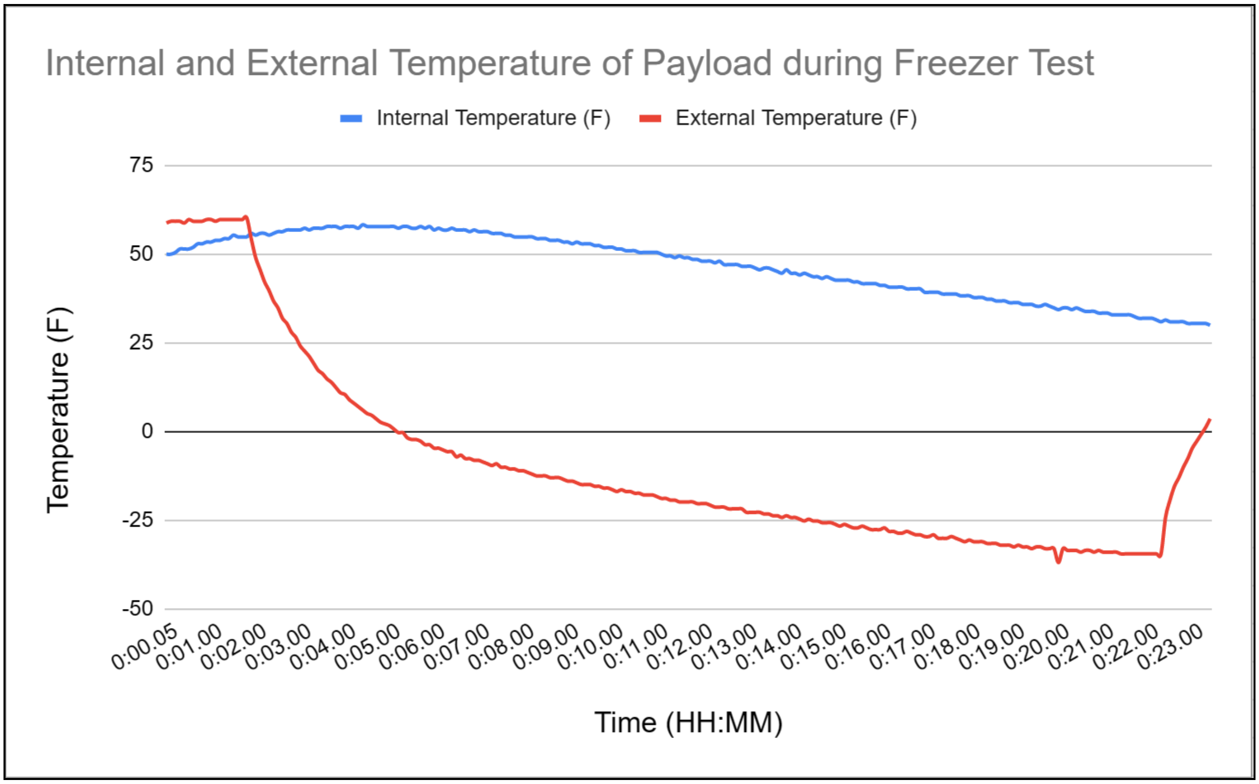

Figure 11. The Internal and External Temperature of the payload during the -80°C freezer test.