High Altitude Student Platform 2021 Final Report

Montana Space Grant Consortium-Montana State University

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Abstract

There is growing interest within the university and light payload balloon community to utilize zero pressure or solar heated balloons to provide extended or long duration flight capability. While the FAA regulations, which are only based on payload weight and not on balloon envelope construction, do not require flight termination capability for payloads conforming to FAR 101 it is highly desirable for balloon operators to possess the ability to terminate the flight of both the payload and balloon envelope for safety and logistical considerations. The Montana Space Grant Consortium (MSGC) balloon program has been developing, refining, and utilizing flight termination systems for the past seven years and has developed a testbed utilizing NASA's High Altitude Student Platform (HASP) to demonstrate and validate the reliability of the termination system under actual long duration flight conditions. The newest rendition of the flight termination system employs two redundant and independent circuits to activate a heated nichrome wire capable of severing the line connecting the balloon and payload. A programmable microcontroller functioning as a countdown timer can execute the termination should communication with the balloon be lost. User-initiated control is accomplished via a command sent to an Iridium 9602 LP satellite modem and relayed to the termination unit via a paired set of low power, shortrange, XBee radios. This termination system is slated to be the system used for the upcoming National Eclipse Ballooning Project.

Introduction

The goal of this project was to develop, test and certify a flight termination system for hand launch high altitude balloons that will be utilized in the NASA 2023/2024 National Eclipse Ballooning Project (NEBP). A part of the NEBP will consist of about 50 teams from universities around the country flying high altitude float balloons during the 2023/2024 eclipse using primarily hardware developed at Montana State University's Montana Space Grant Consortium (MSGC) Balloon Outreach Research and Landscape Imagining System (BOREALIS) lab. The critical detail about the NEBP related to this project is that float balloons will be used. Float balloons are not self-terminating balloons like latex weather balloons are and thus a reliable flight termination system is needed. While the FAA doesn't require the use of a flight termination system for these hand launch balloons NASA does for the NEBP. NASA requires that the flight termination system needs to consist of two redundant and independent systems that are each capable of terminating the flight 100% of the time.

To meet these requirements a new flight termination system was developed based on the previous designs and methods used by BOREALIS successfully for the past decade. This new system has two nearly identical but separate circuits on a single PCB, the only difference between the two is that one is commanded, and the other is timer based. The commanded side uses an XBee3 micro controller combo unit to receive a command to terminate the flight on a local radio network that is ultimately controlled from the ground through the Iridium satellite network. The timer side uses an MSP 430G2230IDR to terminate the flight after a set amount of time. Both sides of the unit are powered by their own lithium AA battery and use a hot nichrome wire to cut the flight line to terminate the flight. The unit is then housed in a waterproof 3D printed box.

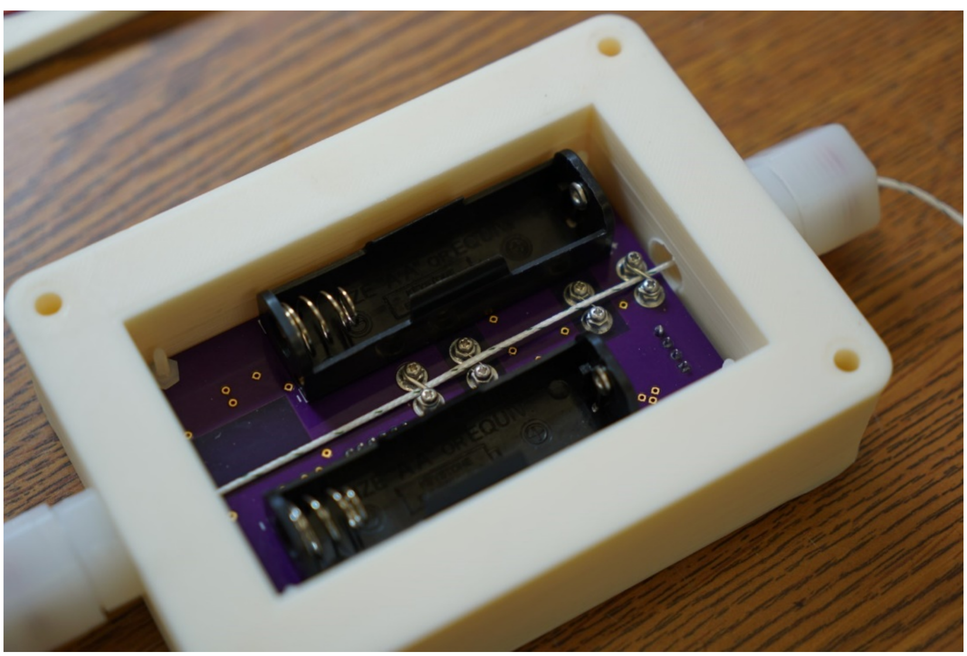


Figure 1: The cutdown device with the line passing through it

For the testing and certification of the flight termination system NASA's High Altitude Student Payload (HASP) program was utilized. HASP allowed work directly with NASA balloon engineers in Palestine Texas using their thermal vacuum chamber for testing and then ultimately fly eight of the units on a

NASA balloon in Fort Sumner New Mexico allowing in flight testing that would not be possible on hand launch balloon flights.

Flight Termination Unit Design

The core of the flight termination unit is a printed circuit board with two independent and isolated termination circuits these circuits are each powered by their own AA battery. A series of 4 gates is lined up in the center of the unit. Each gate is constructed of two SMT nuts soldered to the board. The outside gates are spanned with rigid bus wire while the two innermost gates are spanned with Nichrome 80 wire the selection of the gauge is discussed later. Each nichrome gate facilitates the cutting of the line for one of the two isolated termination circuits. Each system is powered by a single lithium AA battery this 1.5V is then stepped up to 3.3V using a TLV61225 step-up converter. The logic level of 3.3V is used in both systems for the MSP430G2230IDR and the XBee3. To switch the current through the nichrome an MCQ4406 N-channel MOSFET is used. The high current flows directly from the battery through the nichrome and then the MOSFET to ground.

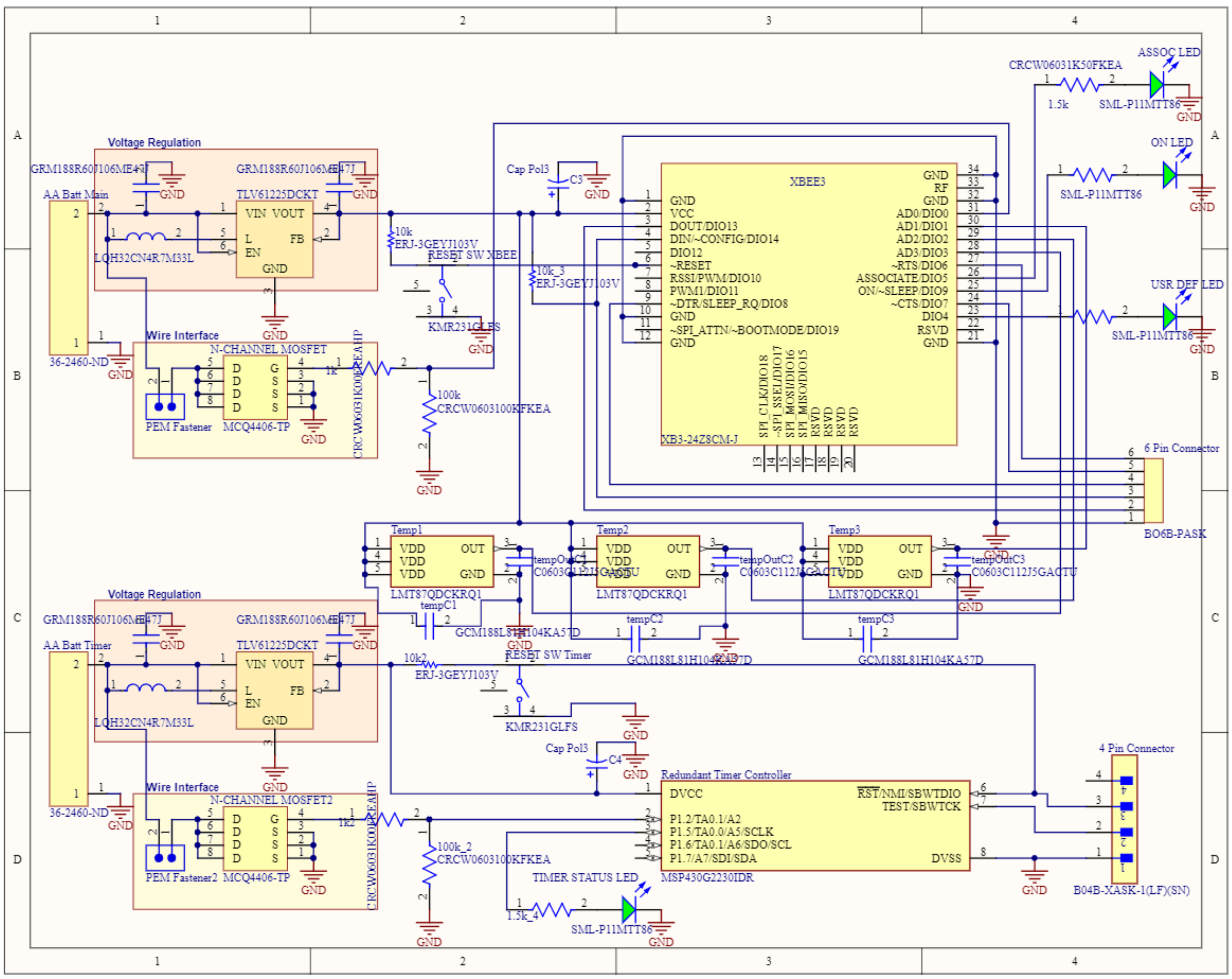


Figure 2: Schematic of the termination system

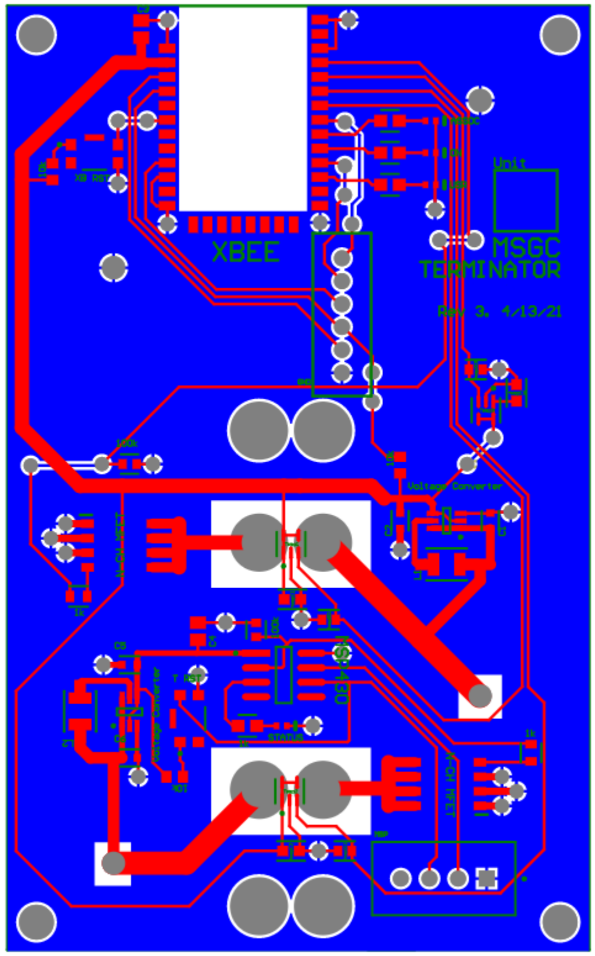


Figure 3: The effects of nichrome wire diameter and wire length on a hot wire cutter

The timer side of the system is controlled by the Texas Instruments microcontroller MSP430G2230IDR. A programmable timer begins counting down when the device gets power. Once the timer runs out the MSP430 triggers the MOSFET and cutdown occurs. This time can be used to set a maximum duration of the flight if communication to the payload is lost the timer can terminate the flight at the set time.

The radio side of the system is controlled by a Digi XBee3 SMT. This SMT radio module communicates at 2.4 GHz on a local XBee network this network allows it to interface with an Iridium modem that allows for satellite communications and control. When termination of the flight is requested the ground team can send a command that is uplinked to the iridium network to the balloon and finally, to the XBee3 the XBee interprets this command and triggers the MOSFET facilitating cutdown. Soley for the validation of this system 3 analog temperature sensors were added to the board and connected to the XBee. Of the three sensors one is for ambient temperature, and one is placed on each of the nichrome gates. This data collection is discussed more below.

The housing that encloses the circuit board is a waterproof box that was designed to be easily 3D printed in three parts out of Acrylonitrile Styrene Acrylate (ASA). It has two lids with O-ring grooves and counterbores for bolts on one lid and for nuts on the other that lie outside of the O-ring grooves. The main housing of the box has two shelves on either side for the board to be bolted to. It also features holes for the bolts to pass through as well as a hole on the side to allow a seatbelt to be tied to the box. The final detail is the two holes on opposite ends intended to be taped so two nylon compression fittings (1/8” NPT - 1/4” tube Parker 2GUW3) can be screwed in. A 9/16” diameter silicon septum is cut from 1/8” thick 50A durometer silicone sheeting and inserted inside the nut of the compression fitting. A sewing awl is used to insert a length of waxed string through the septa. When the awl needle is withdrawn the hole produced shrinks back forming a waterproof seal between the septa and the line. Waxed thread is used to keep water from wicking down the fibers in the line and into the enclosure. For the sake of testing with HASP a slight modification to the box was made in the form of two slits in one of the lids. These slits allowed two pull tabs to be inserted between the batteries allowing the units to be powered on while the box was sealed.

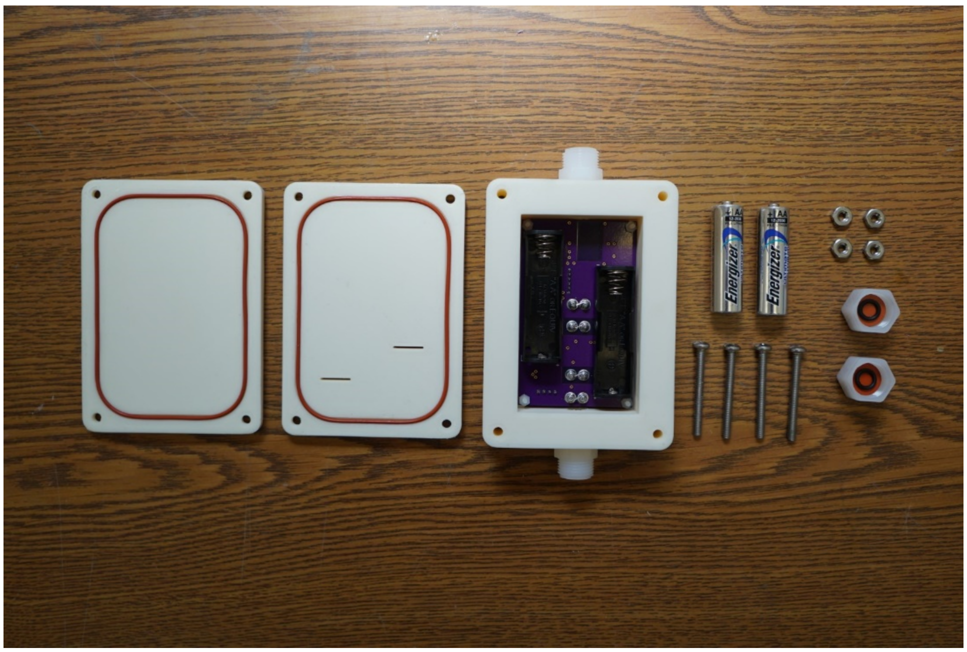


Figure 4: The effects of nichrome wire diameter and wire length on a hot wire cutter

Discoveries, Testing and Changes

One of the first discoveries that threatened the reliability of the system was the discovery of a pulse that occurred at the gate of the MOSFET used for termination on the radio half of the unit. On startup of the ZigBee XBee3, a 300 ms pulse is transmitted from pin DIO12. This undocumented event was found to have the possibility to damage or even cut the flight line when the battery is inserted, or device is powered on, since DIO12 had been selected to drive the gate of XBee3 side MOSFET. Once discovered several solutions were proposed. First, the XBee3 startup sequence was evaluated to investigate whether the pulse could be eliminated in firmware. Given the locked-down nature of the XBee3 device, no such changes could be easily accomplished. The introduction of a large capacitor was also considered. For several reasons, this solution was not suitable because of the need for a similar timeframe intentionally transmitted signals on that line. Finally, other candidate pins were evaluated and pin DIO0 was selected to replace DIO12 as it had no such transient artifacts. A rework of the board was then carried out to switch out the driving pin.

In tackling the problem of creating a reliable flight termination unit, nichrome cutting system tests were conducted to select a suitable gauge of wire at a static length. Initial testing was conducted on a fully built board utilizing new batteries. This test fixture holds the nichrome between two terminals of a fixed distance. 34-gauge Nichrome 80 was initially selected for validation as this gauge had been utilized on a previous similar system that had observed success. Observations of the 34-gauge nichrome 80 concluded that the nichrome while getting visibly extremely hot also resulted in the quick destruction of the wire. This quick burnout of the wire made it highly likely that the line would not be cut. A thicker wire of 32-gauge was then chosen for testing. This wire typically survived 1-2 firing of the wire before breaking and very often cut the line as desired. While 32-gauge nichrome 80 often cuts the line it is highly undesirable for the nichrome wire to break as once it has broken it can no longer be used to cut. Through observation the 30-gauge nichrome 80 provided a hot and reliable burn of the nichrome and subsequently the line. Through all tests the nichrome 30-gauge never failed from burnout or otherwise. Although testing and observations were conducted initially for the purpose of selecting a gauge of nichrome wire these observations continued beyond that selection with the nichrome wire being one of the most observed components of the termination system for the remainder of the project.

A further test of nichrome wire was carried out to flush out understanding of its behavior as it relates to its diameter. Utilizing a high precision ohmmeter (HP 34401A) in 4 lead configuration the conductance of 34, 32, and 30-gauge nichrome 80 was determined. The test fixture utilized a PCB with only the typical nichrome gate terminals. The collected data is recorded in table 1.

In conducting this testing, conclusions were drawn based on empirical evidence and scientific theory. These conclusions will be useful in designing future nichrome-based termination units or designing experiments to further investigate these conclusions.

Table 1: The conductance's of different nichrome wire gauges from testing

Nichrome Wire Size (gauge)	Conductance (ohms/mm)
30	.037
32	.054
34	.092

Design considerations were formulated from these findings and scientific theory and condensed into figure 5. The design effect vectors and their effects on a constant voltage hypothetical system are described below.

- **Mechanical strength –** Mechanical strength of the wire increases with larger wire diameter and shorter length. Increasing this strength allows for the wire to withstand higher forces while not firing. If the wire cannot withstand the forces exerted, then the wire may break or deform in a way that may jeopardize the capability of the wire to perform its necessary functions.
- **Thermal Creep –** Creep decreases as larger wire diameter as both decreasing temperature and increased mechanical strength work to reduce the effects of high heat in deformation of the nichrome. Thermal creep can deform the wire requiring it to be replaced between firings.
- **Break While Cutting –** Nichrome is less likely to break (burn up) while cutting with reduced temperature coming from both larger wire diameter and length. If the melting point is avoided the nichrome will not burn up or break. This burn up condition severity reduces effectiveness of a cut and requires replacement to be fired again. This burn-up should be avoided as the primary design consideration.

- **Power Required –** The power required reduces with resistance as voltage is held constant in this hypothetical system. Power required reduces with increased length of wire and reduced wire diameter.
- **Temperature –** Temperature increases with reduced diameter and wire length. Sufficient temperature is required to burn and cut and the line and is therefore particularly important to reliability.

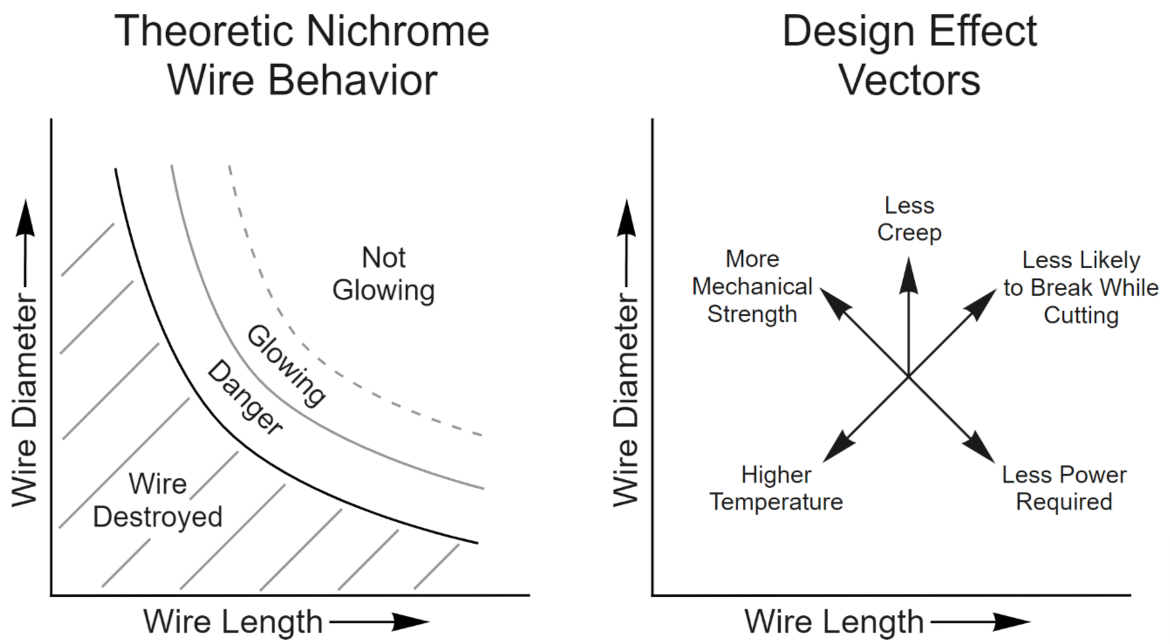


Figure 5: The effects of nichrome wire diameter and wire length on a hot wire cutter

In preliminary duration testing, it was seen that the voltage of the battery drooped with extended time and low temperature. This was further substantiated in the thermal vacuum testing discussed below. This lower voltage was perceived as a threat to the reliability of the system since it had also been observed that the battery voltage could drop further when the nichrome was turned on for 10 seconds. The threat to system integrity involved the possibility of a brownout of the system just as the termination sequence began. This brownout would cause the microcontroller to restart or could cause unforeseeable results. This issue would affect both the XBee3 and MSP430 systems. To reduce the chance of such an event the MOSFET was driven with 10 pulses lasting 10 seconds with a duty cycle of 30%. These pulses were seen to give a chance for the battery voltage to recover and would allow the nichrome to chip its way through the line even at low power output. A first duty cycle of 30% was chosen as it appeared to allow for a consistent cut while supplying time for battery recovery. Thermal vacuum testing later showed that a higher duty cycle would be needed to ensure good termination at extreme temperatures while some benefit of the duty cycle remains.

To guarantee the operation of the complete system, including data collection before thermal vacuum testing, a long freezer test was performed. This evaluation tested the reliability of the data collection performance of the system over long duration at low temperatures. The results of this test highlighted a bug in the data collection system that would randomly restart the XBee that preforms data requests. This issue was tracked down to noise in the interaction between a step-down DC-DC converter and the step-up circuit on the hasp interface board. This noise would intermittently spike the voltage to ~4V (above the spec range) causing the XBee3 to perform a shutdown procedure to protect itself. This issue was resolved by removing the unnecessary step-up circuit from the system. This power conversion system is discussed in more detail below.

High Altitude Student Platform Testing

NASA's HASP program was a unique opportunity that gave access to testing methods that would not have been typically available. HASP allowed two six-hour tests in their thermal vacuum chamber which was able to simulate environments even more extreme than during an actual flight (-60 to 60°C) and to fly eight flight termination units for a 16-hour flight at 120,000ft of altitude. This is both higher and longer than anything that could have been accomplished at a college level.

To fully take advantage of the HASP program a rigorous and redundant test procedure was required to be developed for the autonomous testing of termination subsystems. Just like the flight termination units themselves, the test procedure had to allow for backup methods. This redundancy allows confident detection that the system functioned correctly using several different methods ensuring data robustness. Additionally, if a failure of the system occurred in flight a cause of failure would need to be discerned. To give the best picture of such an event these redundant systems are in place to capture maximum information about the system from the two sides such that any resulting investigation can be as thorough as possible. These methods allow meaningful studies to be conducted demonstrating the effectiveness of the flight termination unit especially when the tests occur far above the laboratory and out of view.

The first and primary way of collecting data was the use of a Mechanical Onboard Unpowered Signal Equipment for Testing Radio Actuated Payload (MOUSE TRAP). The MOUSE TRAP served two purposes, to simulate the tension in the string that occurs during an actual flight and to serve as a mechanical flag that would indicate the termination system as correctly fired. It was found during early testing that the silicon septa in the box's fittings offered enough resistance that the MOUSE TRAP was unable to pull the string far enough through to activate the mechanical flag and this the septa were removed for testing (Note that the septa do not create a similar issue during actual flight operation). During all HASP testing units were observable either by cameras on the flight or through the window of the thermal vacuum chamber. The mechanical flags were always the first confirmation of a successful simulated flight termination.

The second way of collecting data was the use of three temperature sensors on the board. The temperature sensor used is the Texas Instruments LMT87QDCKRQ1 analog temperature sensor. As aforementioned one temperature sensor was placed under each nichrome wire and the third off to the side as a baseline/ambient reading. This analog value was read by the XBee3's 12-bit ADC it was then converted into Celsius using the equation found in the device datasheet. This temperature data was then communicated over the XBee's to a central XBee that could then send that data down to the ground via NASA/HASP's flight systems. This did, unfortunately, suffer from about a ten-minute delay in packets of data due to how the ground link worked. Deciphering this temperature data was relatively simple, a spike in temperature on one of the sensors under a nichrome wire indicated the wire fired and heated up to cut.

The third and final method for collecting data was the physical observation of the string after testing. The broken ends of the string were looked at under a microscope to ensure the string was cut by the hot nichrome wire and did not break some other way. Of course, after one of the nichrome wires was fired the MOUSE TRAP would pull the string out. This obviously creates a problem as it would not allow observation if the string were cut by the other nichrome wire. To get around this issue one silicon septa was added back to the box and added Kapton tape in between the two nichrome wires to hold the string down in place. Which side the septa was added to, as well as the direction the MOUSE TRAP faced, was dictated by the unit having the commanded or timer side of the termination unit to fire first. The use of a single septum and Kapton tape allowed observation of the mechanical signaling of the MOUSE TRAP as well as observe the string cut in both places by the two nichrome wires.

With the three data collecting methods established the final testing procedure could be produced for both the thermal vacuum testing as well as the actual flight. Procedure for testing in Palestine, TX can be found in appendix A and the procedure for the flight in Fort Sumner, NM in appendix B.

The final key for using HASP was the creation of a centralized payload that conforms to HASP's standardized size. The specifications of the termination units themselves would be attached around the HASP payload gondola with hose clamps. The central payload consisted of four main components: the preexisting Iridium unit, a power converter board to power the iridium with HASP's provided power instead of the usual batteries used, the central XBee to receive the temperature data from the termination units and a solar shield.

Power is provided to the payload plate at 30V DC to power the Iridium and central XBee unit. A power converter board had to be implemented which takes 30V and regulates it to 5V and 3.3V. The system uses 2 Texas Instruments adjustable switching regulators PTN78060WAH and PTH04000WAH these regulators create the required voltage in the configuration in Figure 6.

With the correct voltages generated the Iridium modem can receive and retransmit commands sent through the Iridium network. This system uses a proven in-house control board known as OCCAMS to facilitate the translation between the Iridium modem and the XBee command. This XBee also acts as the host of the network as it is the center of communication in typical flight applications.

The other remaining element of the payload plate is the central or master XBee. This XBee regularly polled each of the units requesting temperature data the units then respond with their individual temperature readings. This data is then processed, timestamped and transmitted via RS-232 to the DB9 connector on the payload plate where it is downlinked and logged on HASP servers.

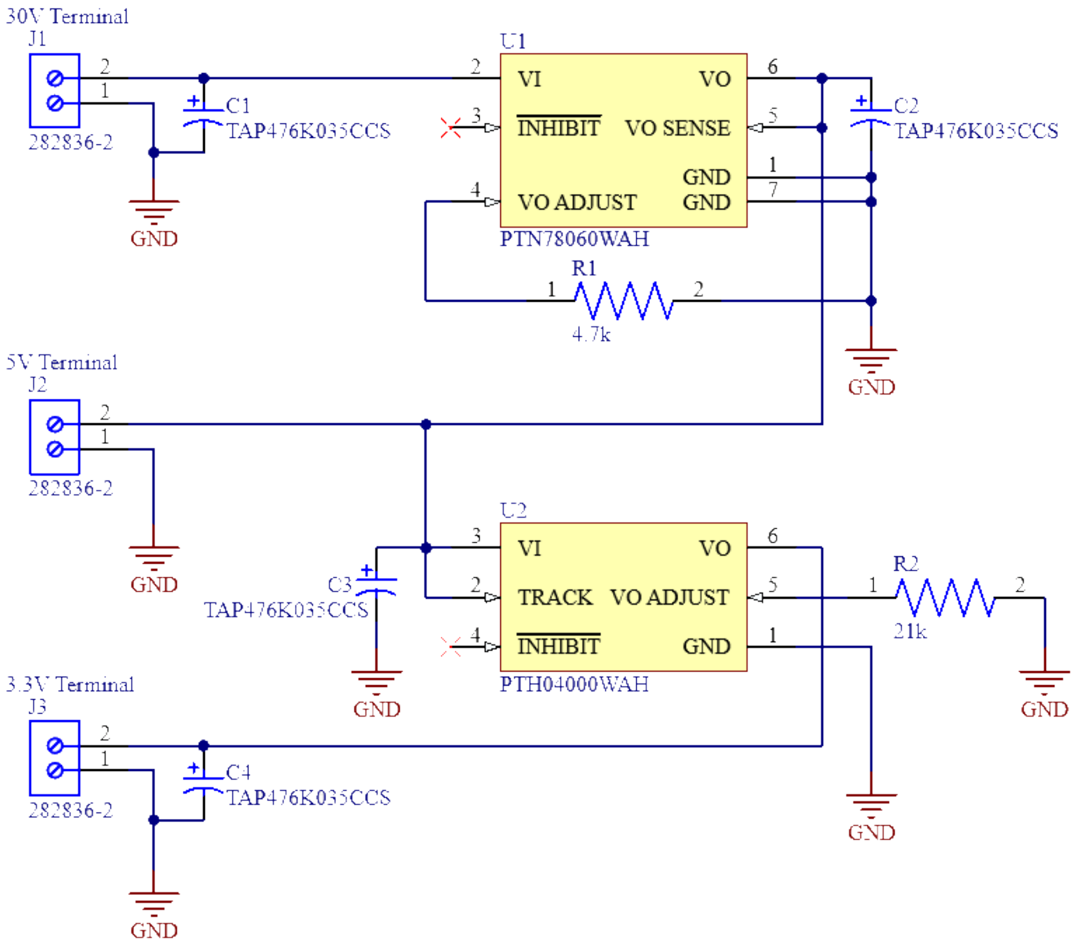


Figure 6: Schematic of power supply board

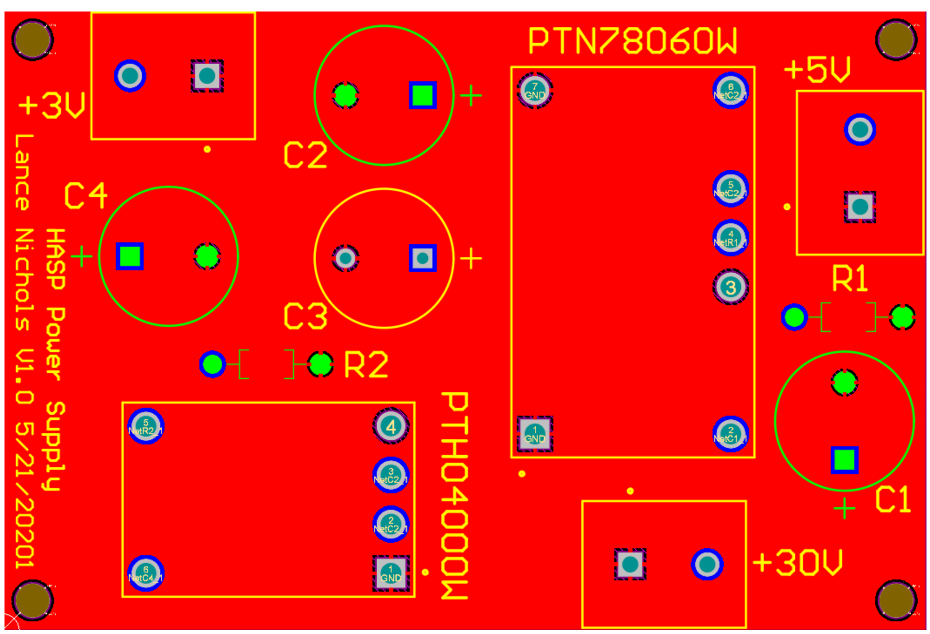


Figure 7: Layout of power supply board

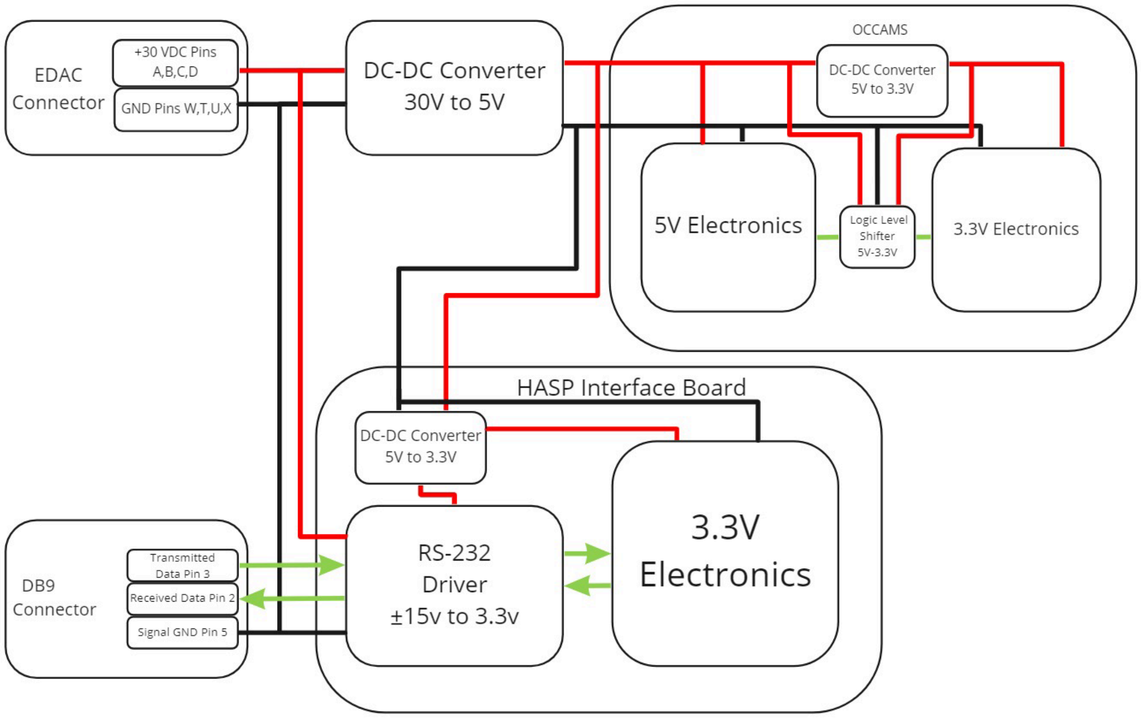


Figure 8: Payload plate interface and power distribution

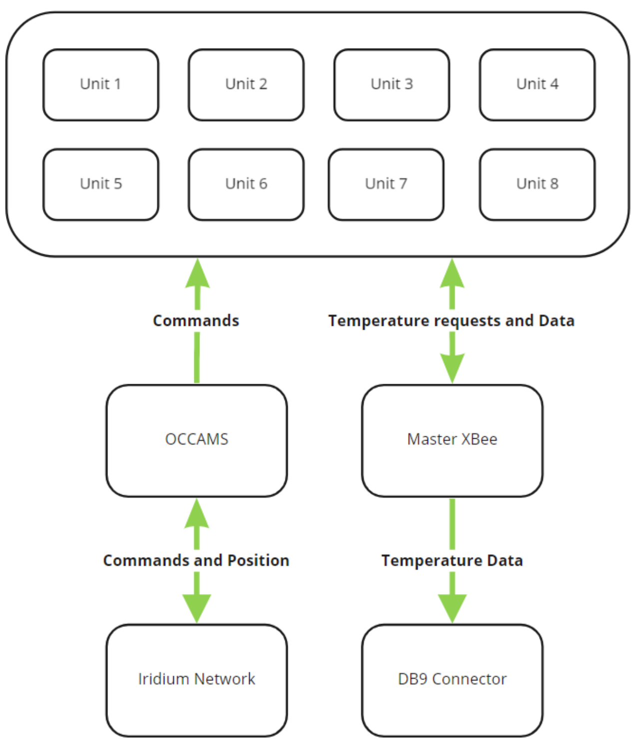


Figure 9: Data flow diagram

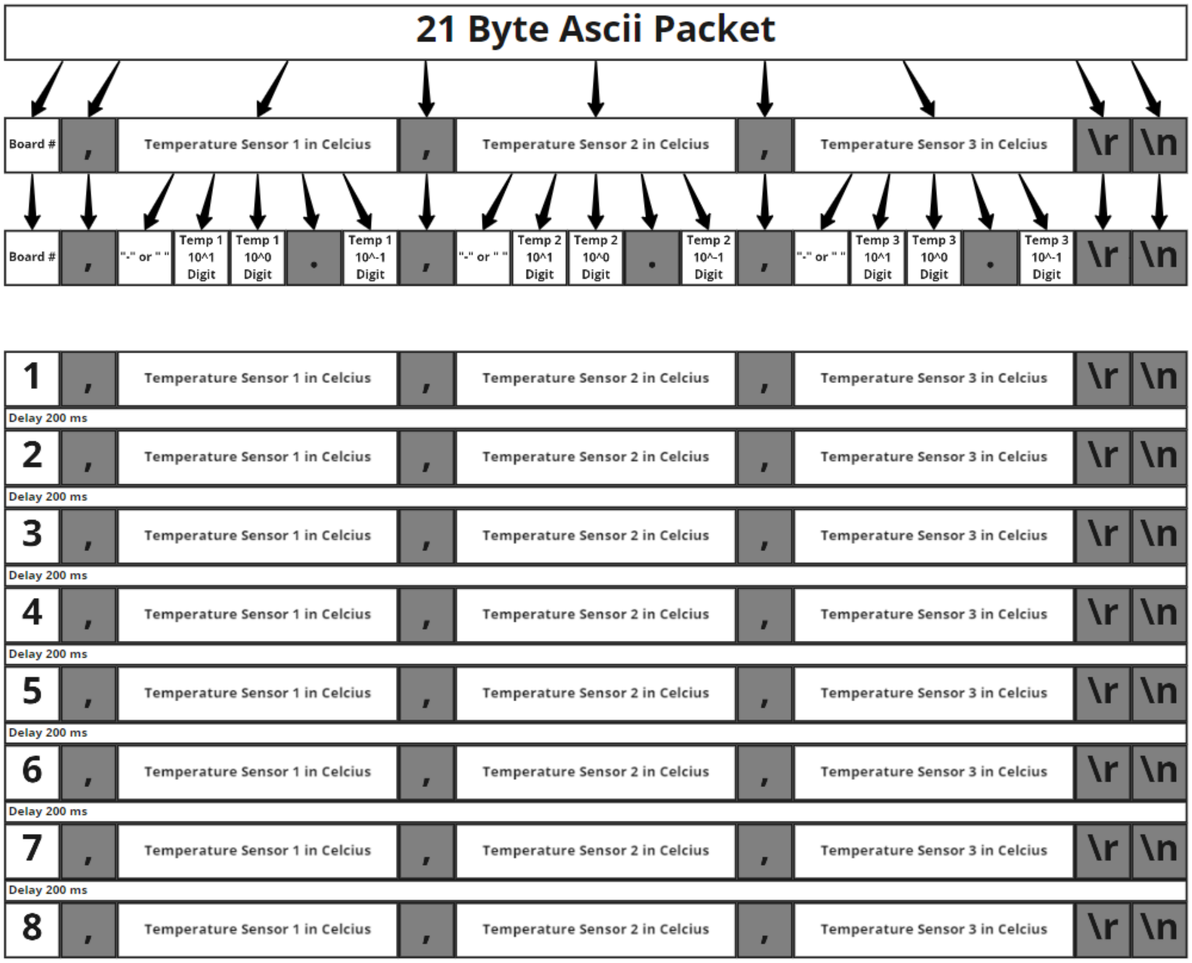


Figure 10: Serial packet construction without timestamp

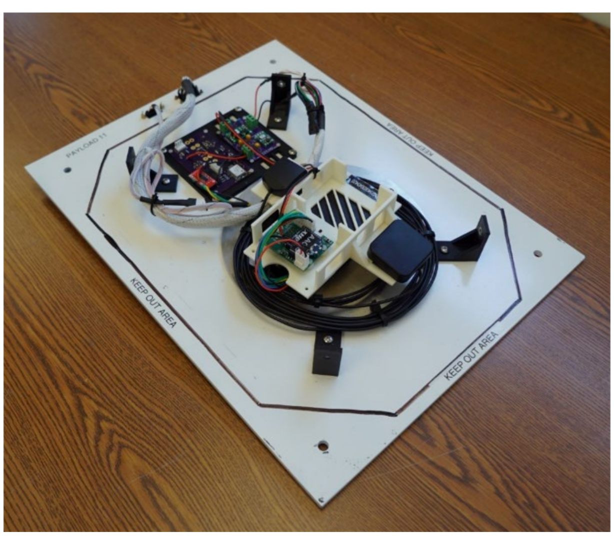


Figure 11: HASP payload plate without solar shield

Figure 12: HASP payload plate with solar shield

Palestine, TX Results, Data and Changes

Thermal vacuum testing and flight verification in Palestine TX allowed for two extreme environment testing opportunities before the flight. This environment allowed for a refining of the system and further system verification. The first thermal vacuum test followed the detailed procedures that can be found in Appendix A. All hot side units cut the lines as expected but no cold side units were able to cut the line even after repeated firings. After the test had been completed the cold side units were inspected and it was found that the nichrome was melting the string where it touched but was not severing it. It was concluded that the nichrome was not getting hot enough in the extreme low temperature environment.

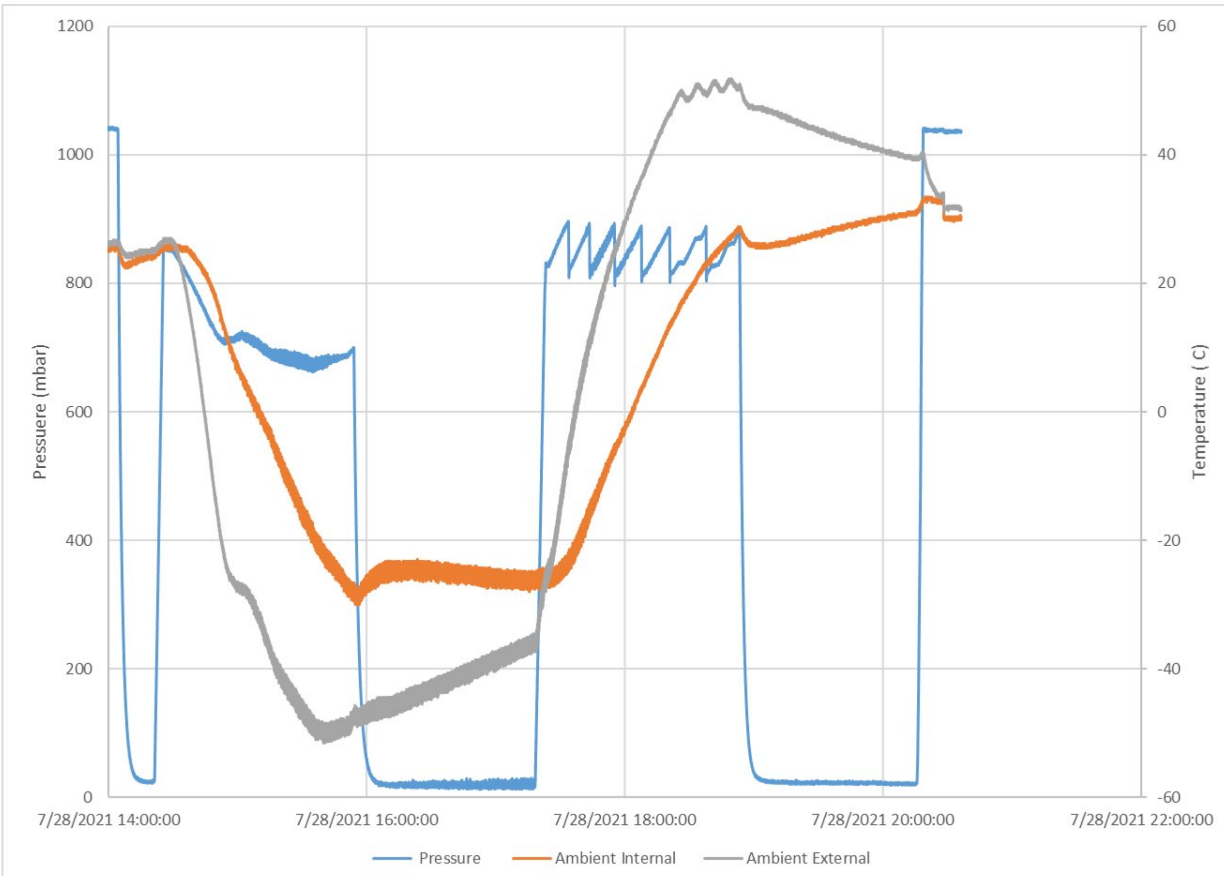


Figure 13: Thermal vacuum test one temperature and pressure profiles collected by CSBF

The second thermal vacuum test focused on understanding and overcoming this issue. Six of the eight units were set to trigger on the cold side with a range of duty cycles selected. The selected values were: 50%, 60%, 70%, 80%, 90%, 100%. All but the 50% duty cycle successfully cut the cold side line on the first try. The 50% duty cycle did eventually terminate after two more firing attempts. Based on this performance and taking into account the voltage drooping mitigation it was decided that a duty cycle of 70% would be selected for all future usage.

The second thermal vacuum test also allowed for some data collection on the behavior of the AA batteries. The battery voltage of the commanded side of two of the units is plotted in Figure 15. When the temperature decreased in the chamber the voltage of the batteries dropped by almost 0.2 volts. When the nichrome fired, and the battery was connected across the nichrome it was observed that the voltage would drop as low as 0.45 volts. Fortunately, the TLV61225 step-up converter was able to keep an uninterrupted 3.3-volt output despite the overall lower voltage and the momentary voltage drops.

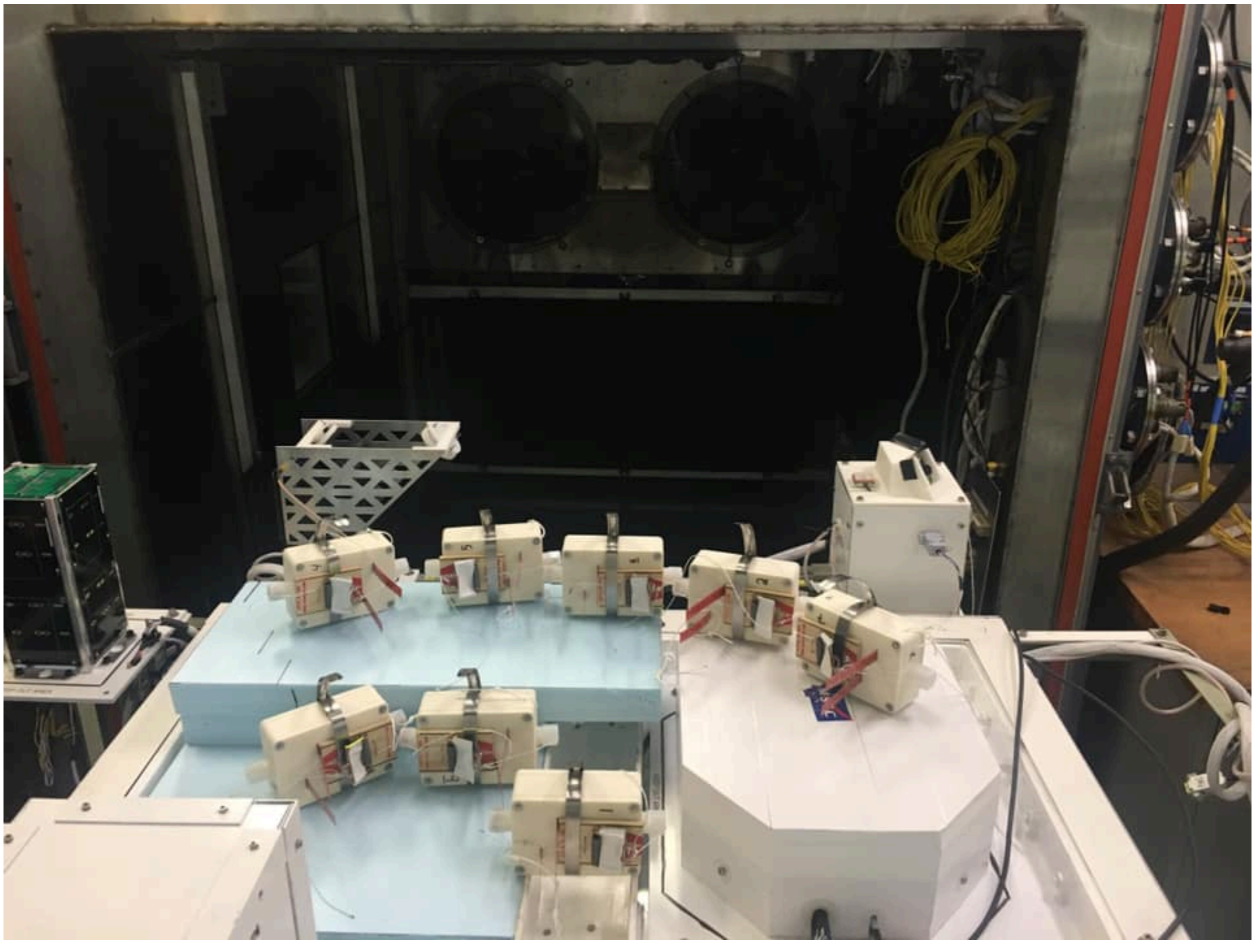


Figure 14: Cutdown units arranged inside on top of the HASP payload for thermal vacuum testing

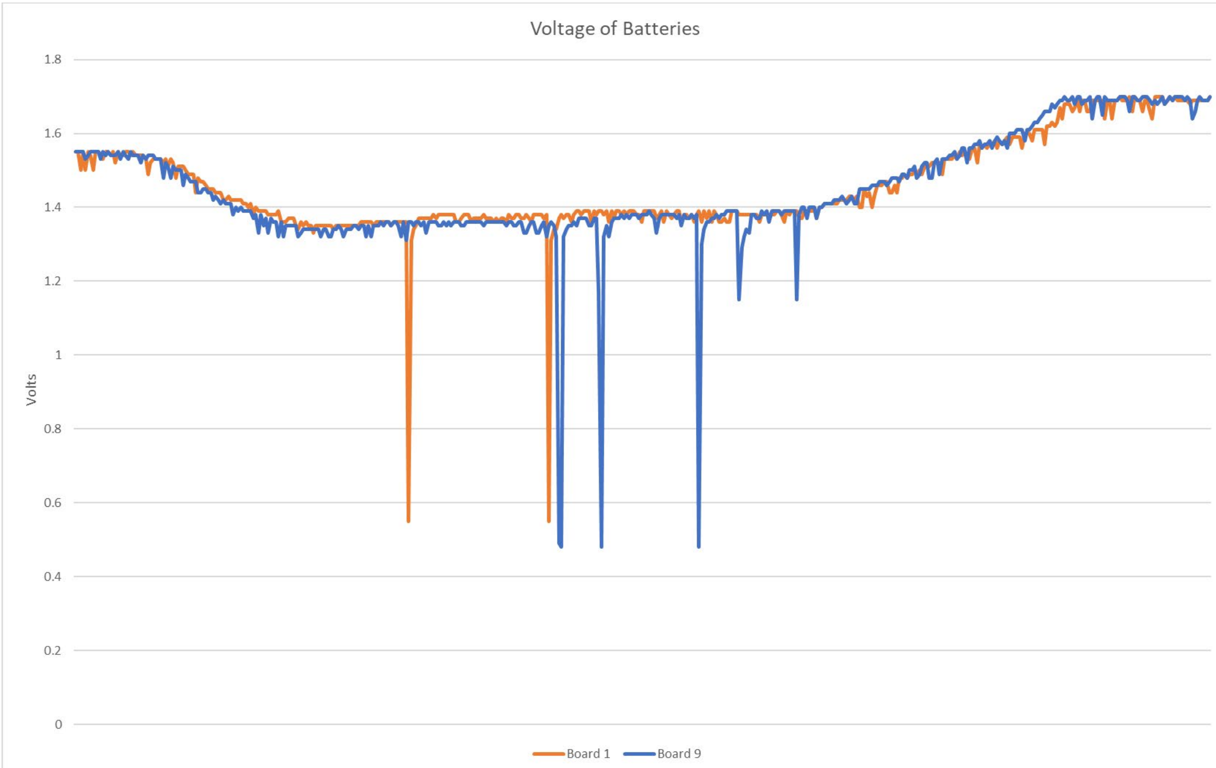


Figure 15: Commanded side battery voltages during cold soak

Fort Sumner, NM Results and Data

The following 16 graphs are the temperature data from the flight. There are two graphs for each unit, the first of those two shows the data from the entire flight. The second shows a zoomed-in view of the same data highlighting the temperature spikes that indicate a termination system has fired. Some of the graphs also show some temperature spikes that are not visible in the second of the two graphs. These spikes are simply single data point errors from a lost packet when transmitting the data and should be ignored. Additionally, each initial firing of the cutdown (i.e., the first temperature spike that is not an error) resulted in the activation of the mechanical flag of MOUSE TRAP, which was visible from remote cameras on the balloon. With excitement, it is reported that both the live video and temperature data collected during the flight correlated perfectly together for each flight termination system. This suggests that each unit performed correctly.

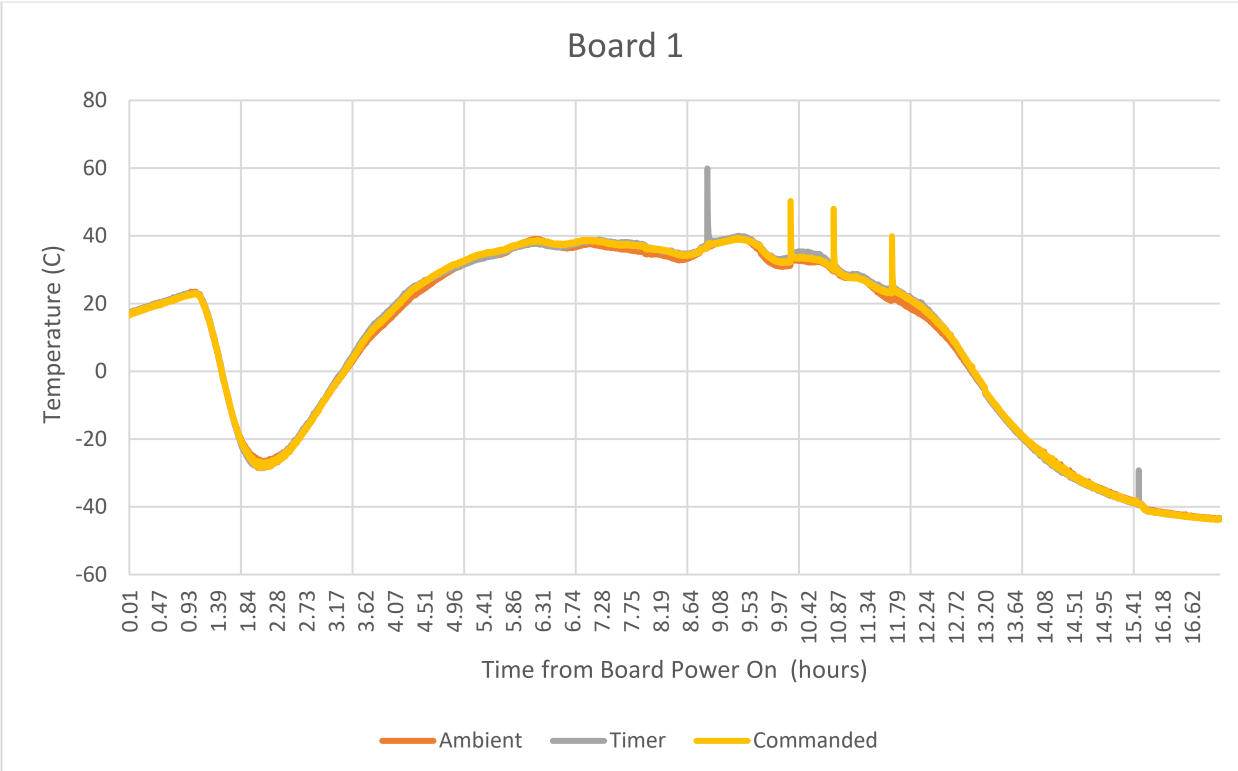


Figure 16: Board 1 temperature over the flight

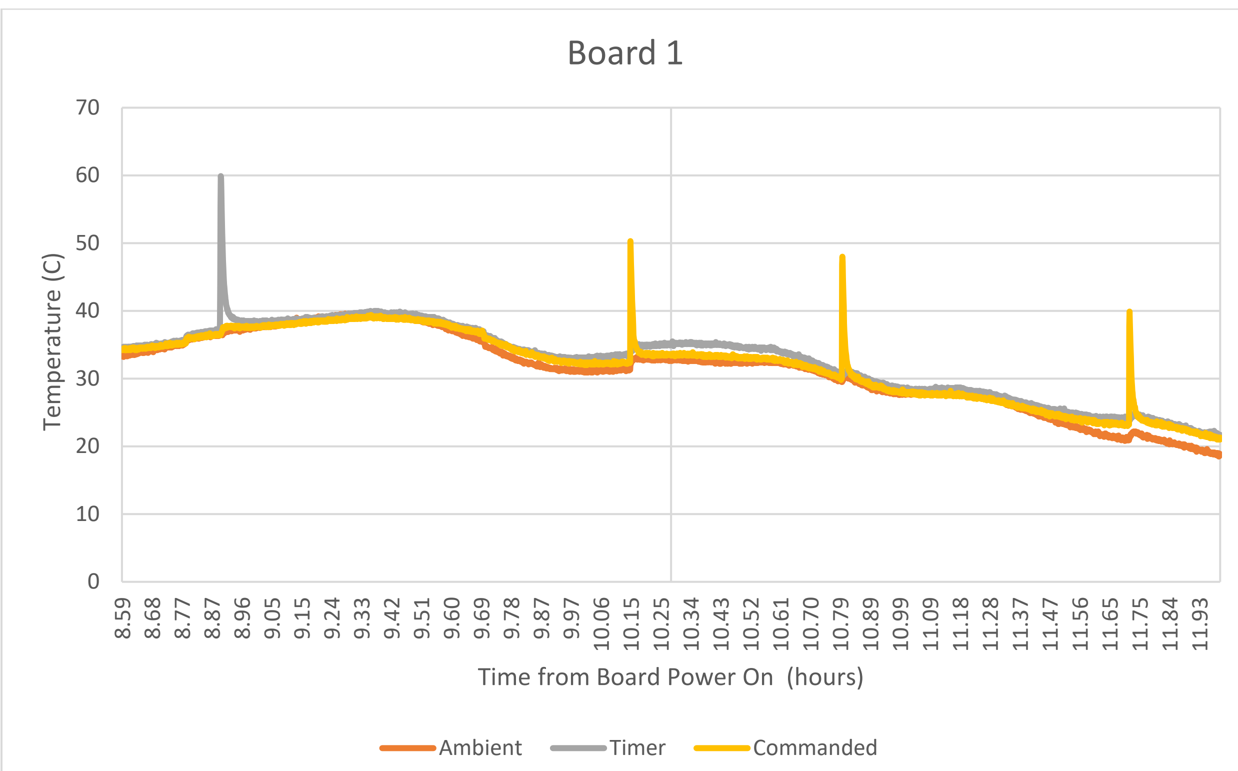


Figure 17: Board 1 temperature at time of interest

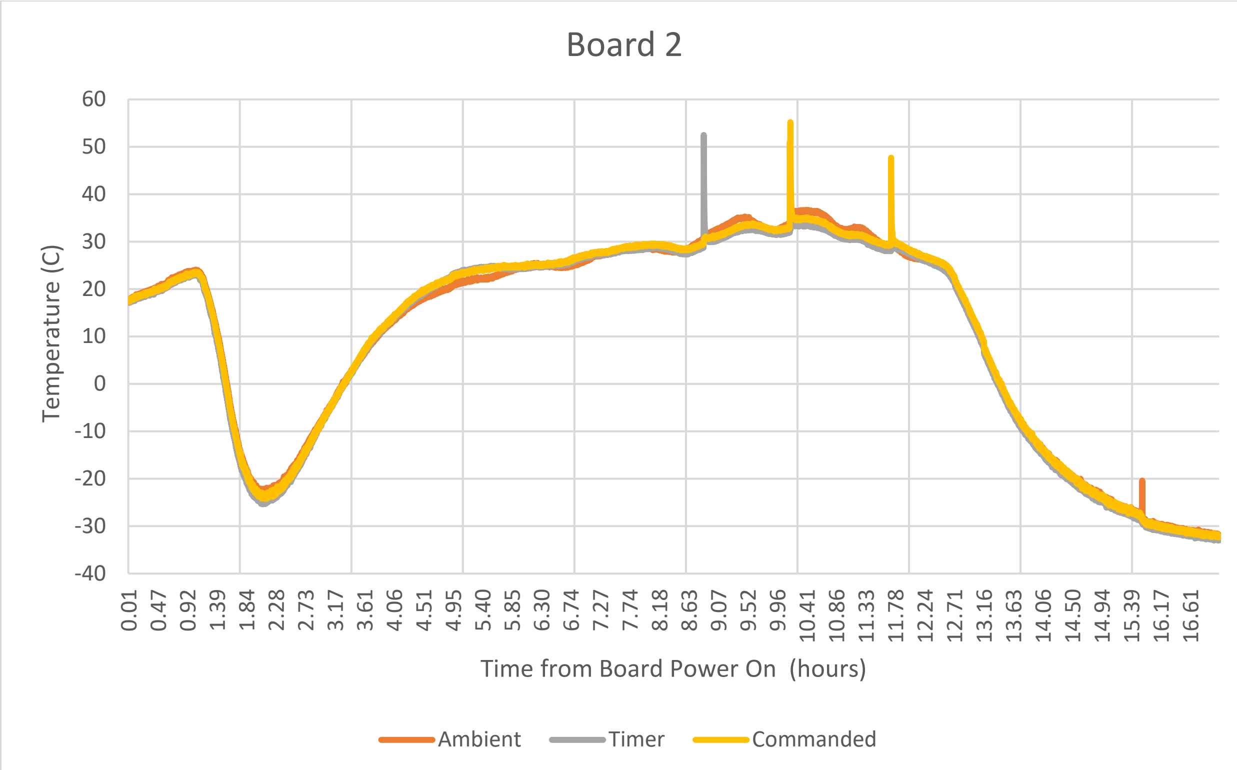


Figure 18: Board 2 temperature over the flight

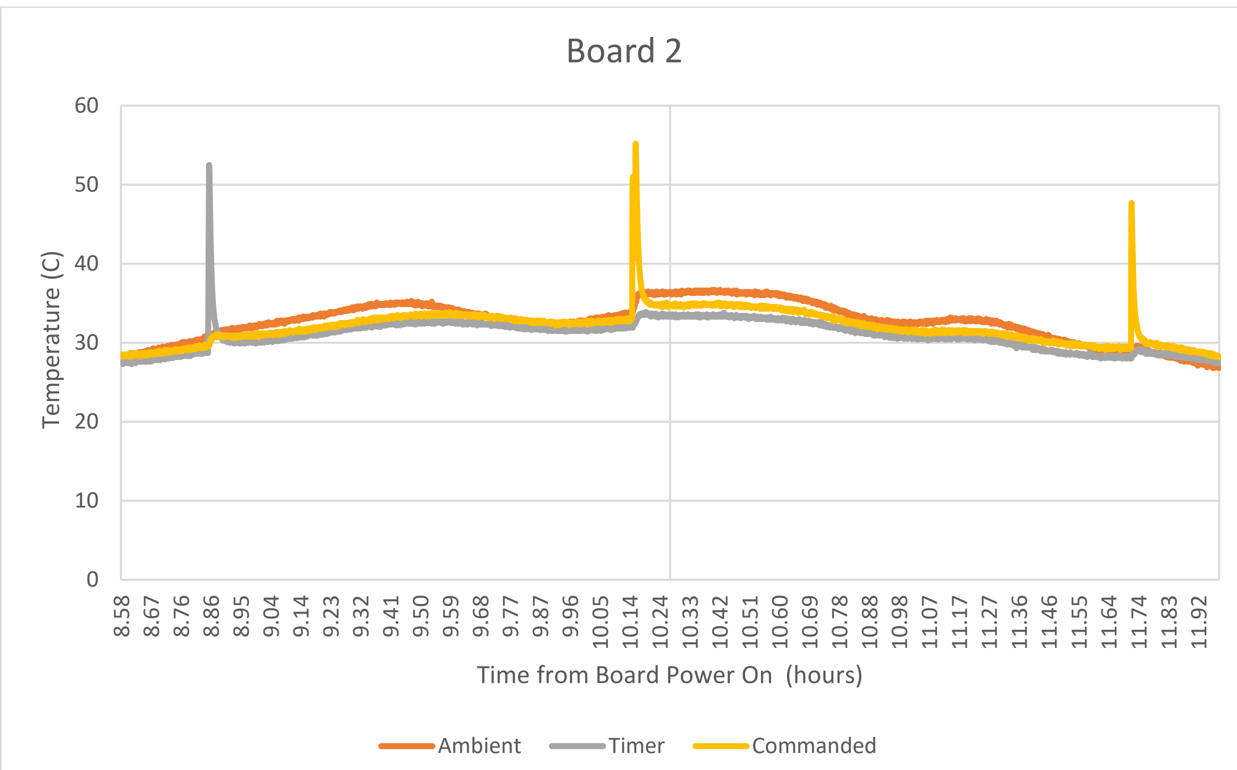


Figure 19: Board 2 temperature at time of interest

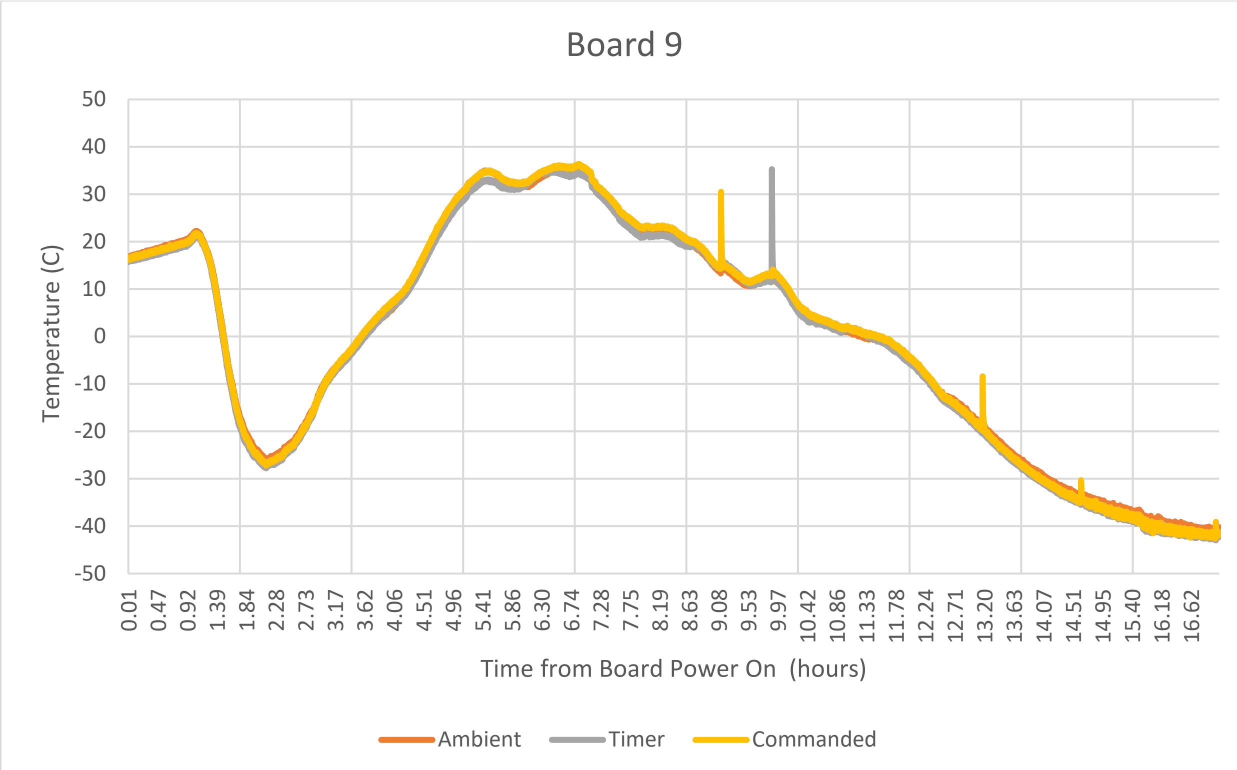


Figure 20: Board 9 temperature over the flight

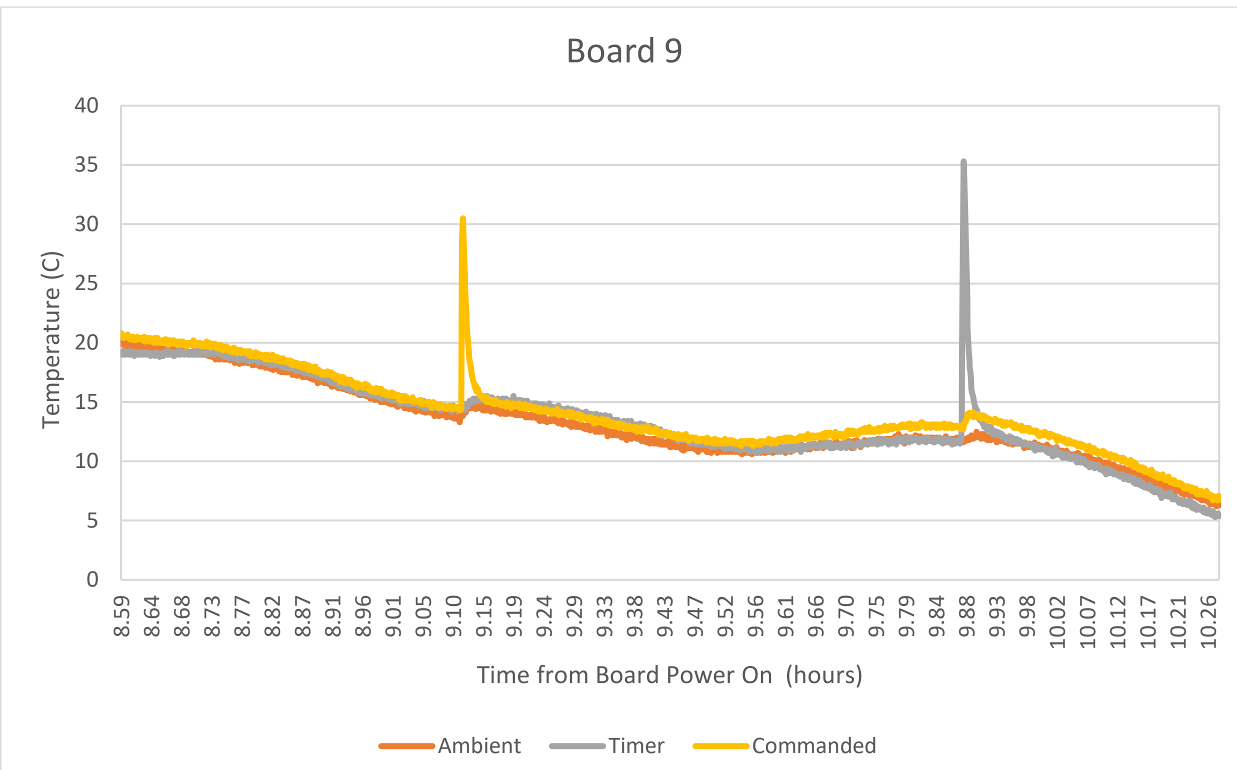


Figure 21: Board 9 temperature at time of interest

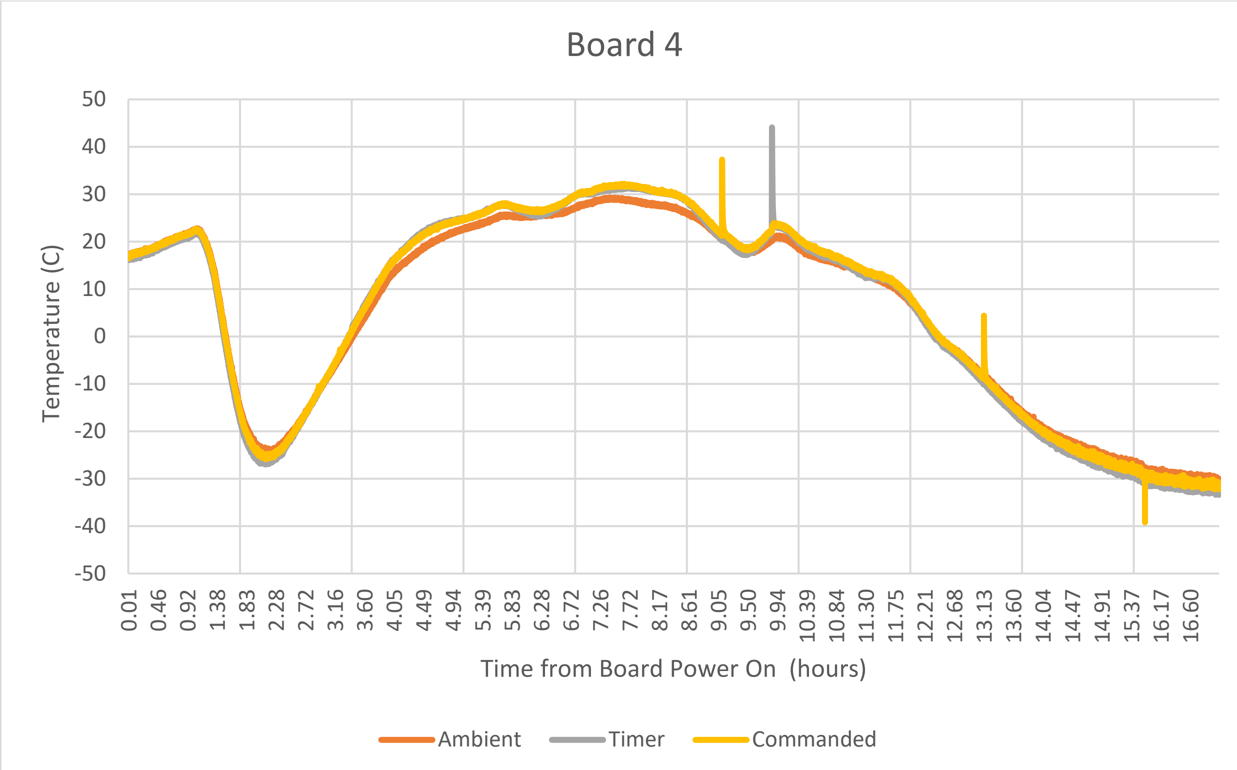


Figure 22: Board 4 temperature over the flight

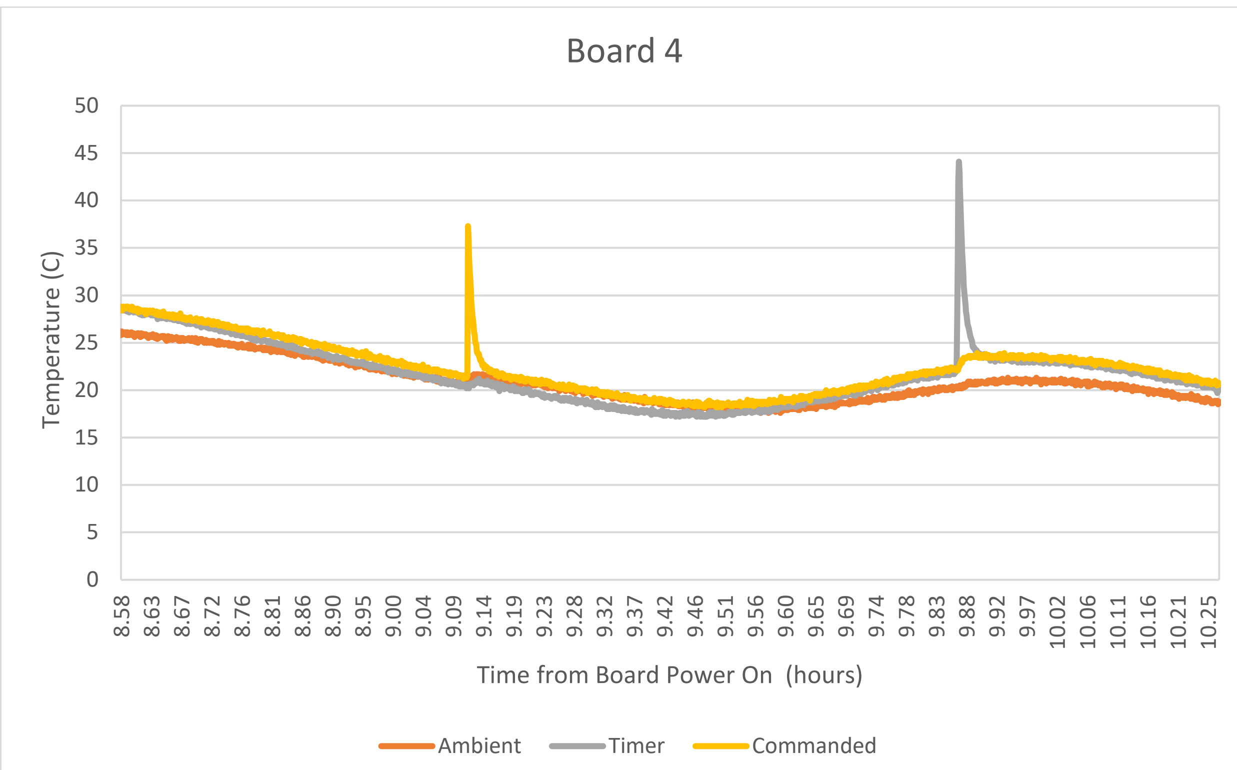


Figure 23: Board 4 temperature at time of interest

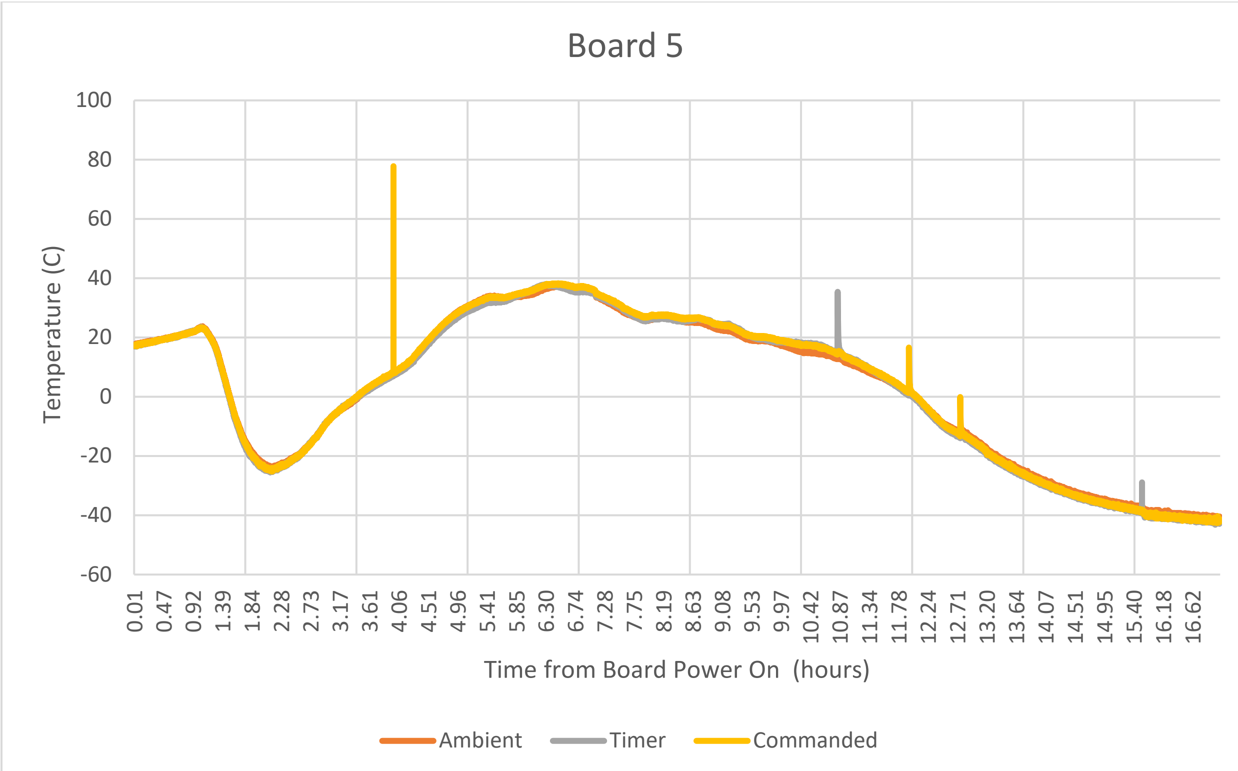


Figure 24: Board 5 temperature over the flight

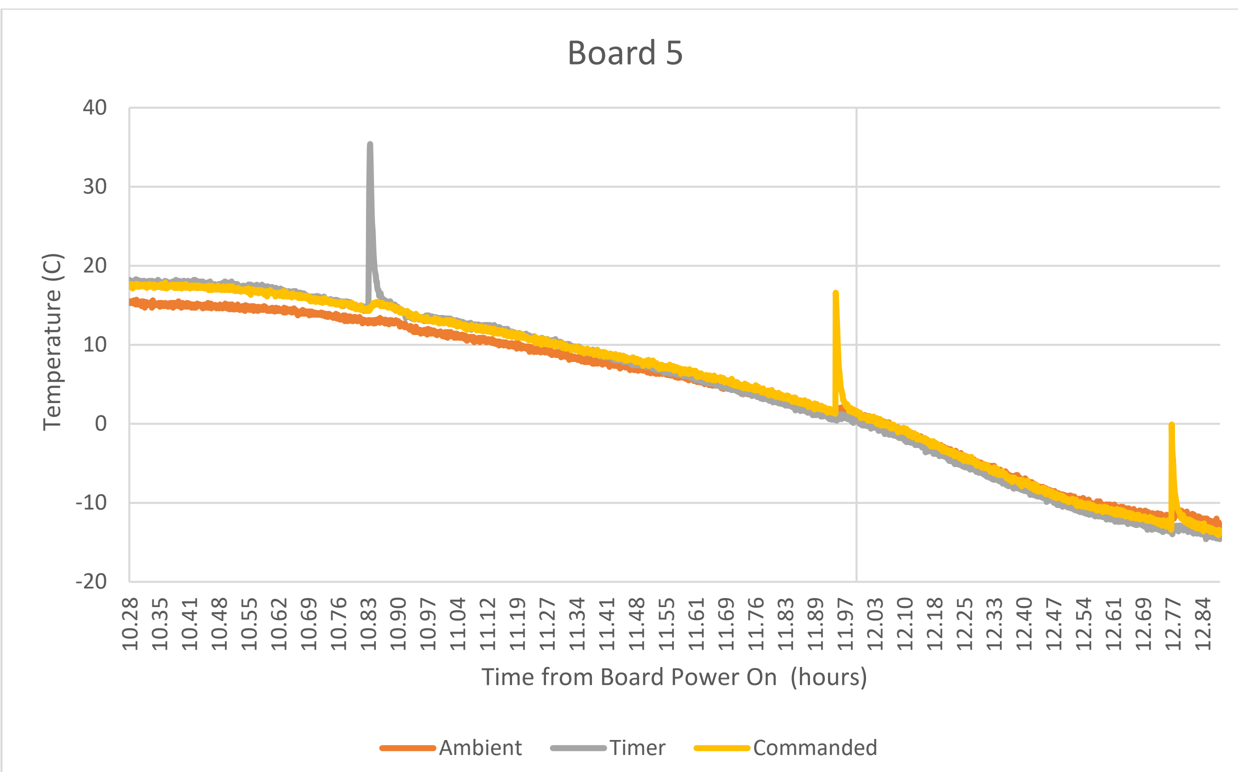


Figure 25: Board 5 temperature at time of interest

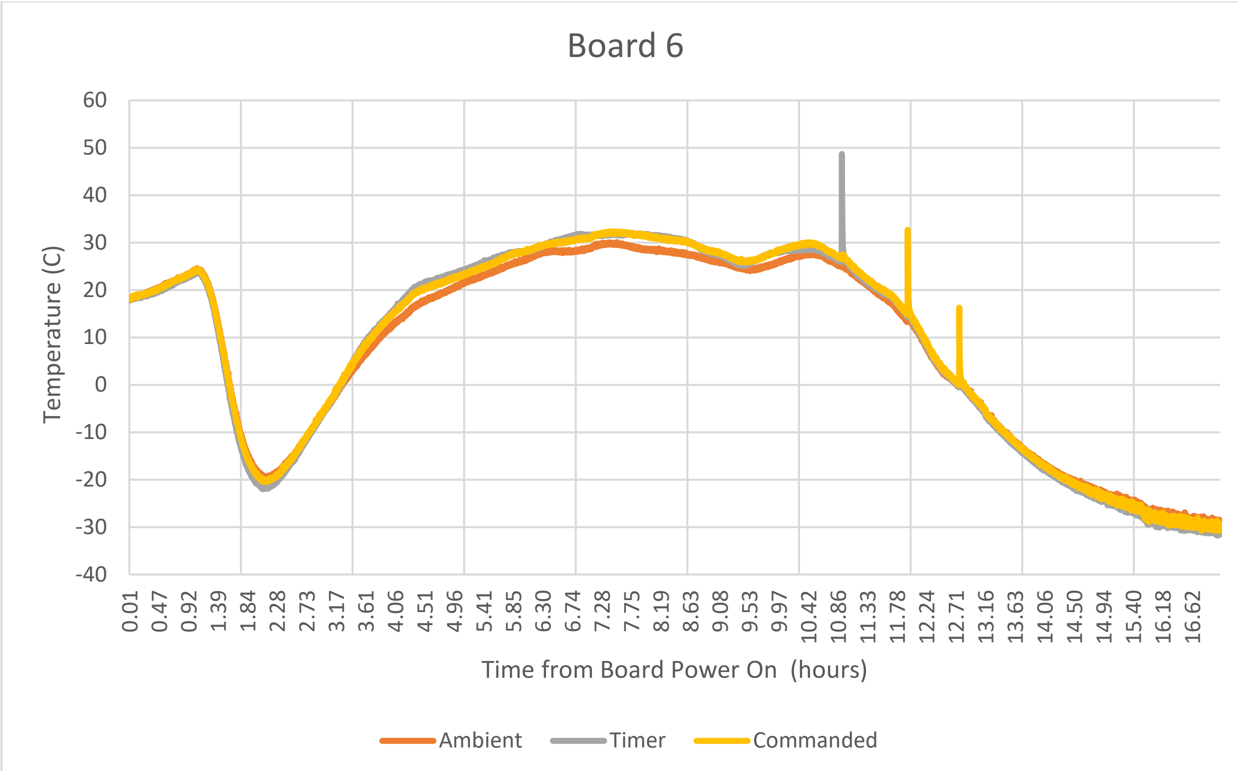


Figure 26: Board 6 temperature over the flight

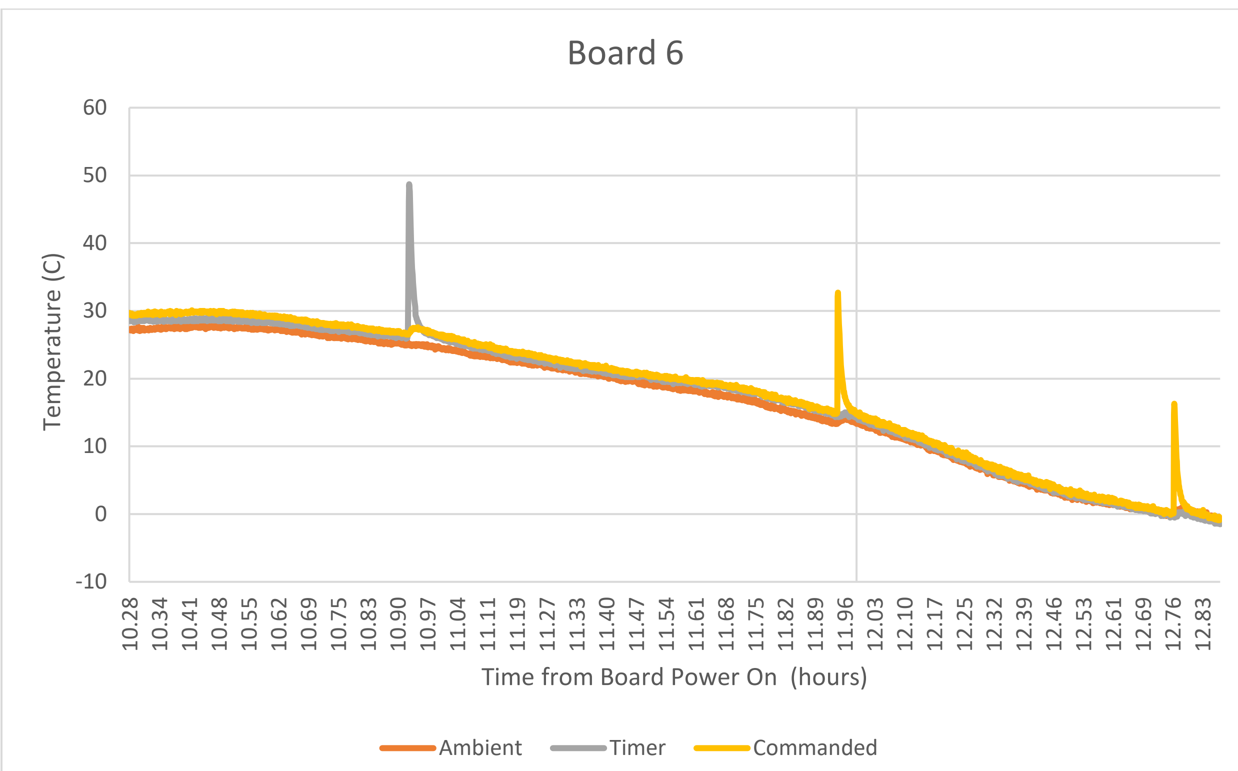


Figure 27: Board 6 temperature at time of interest

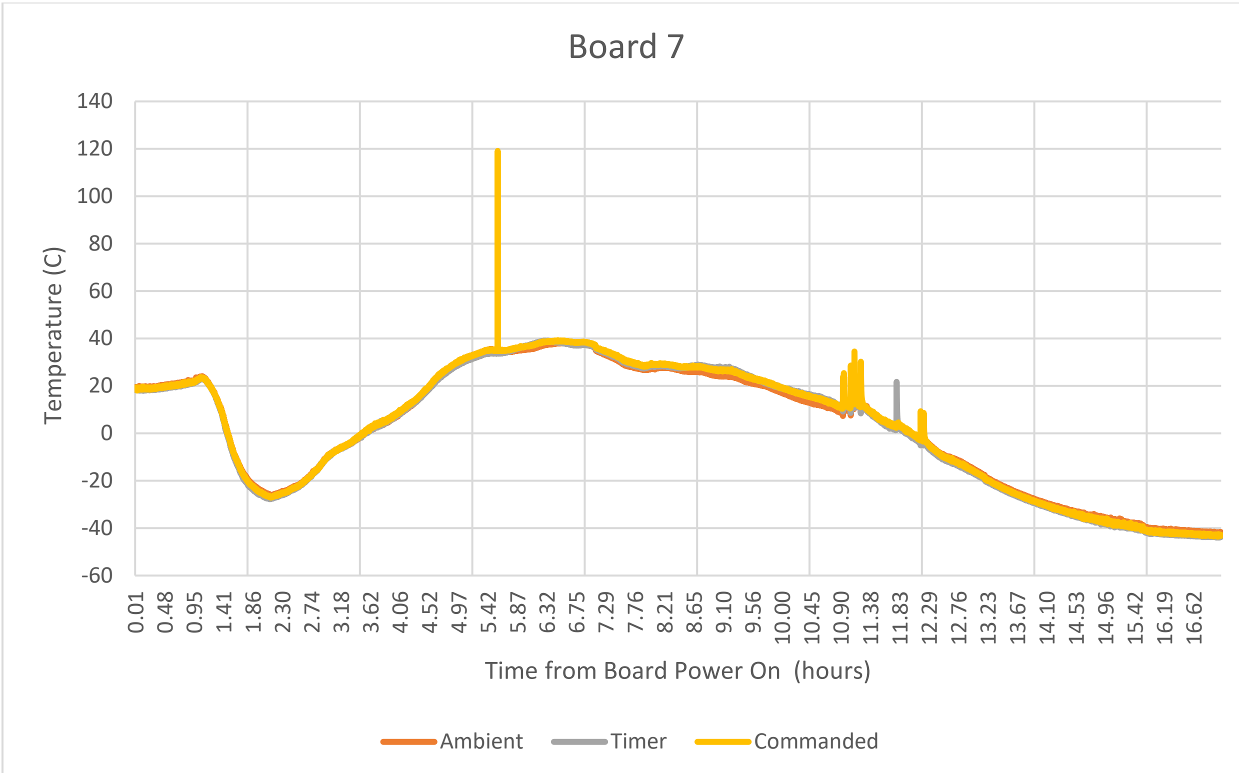


Figure 28: Board 7 temperature over the flight

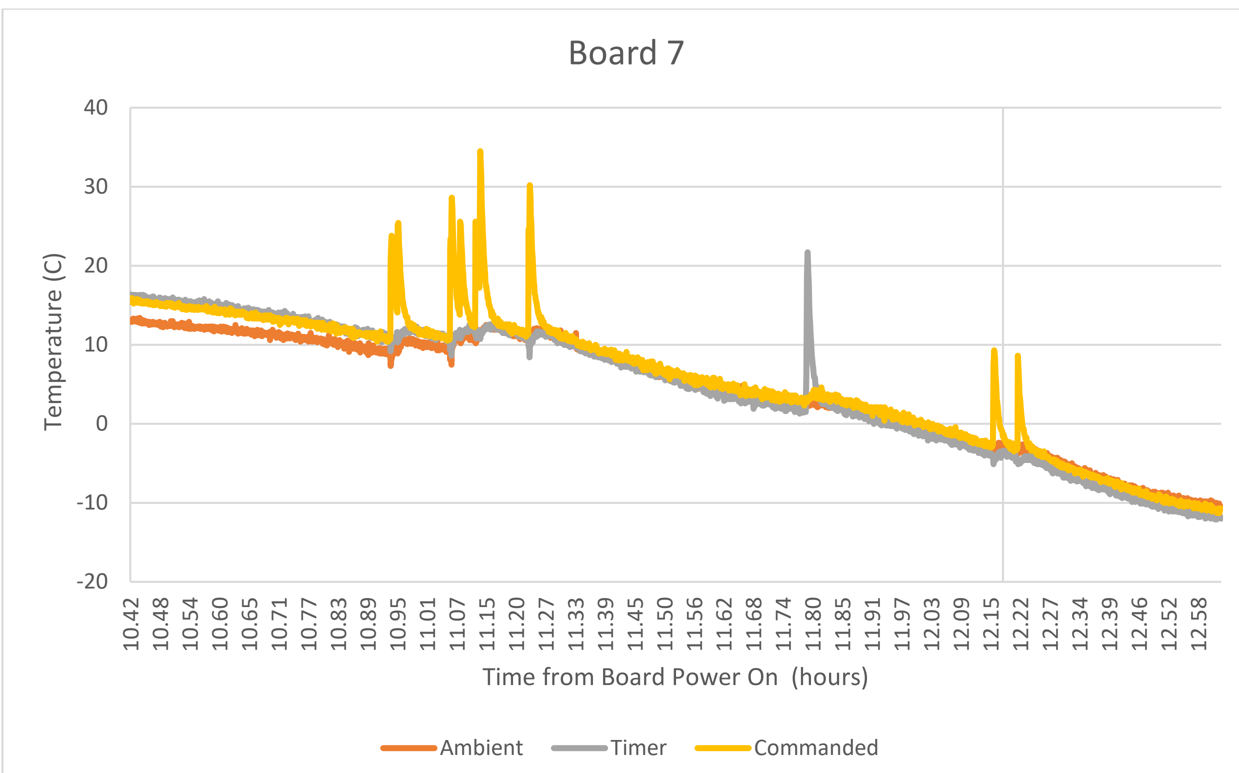


Figure 29: Board 7 temperature at time of interest

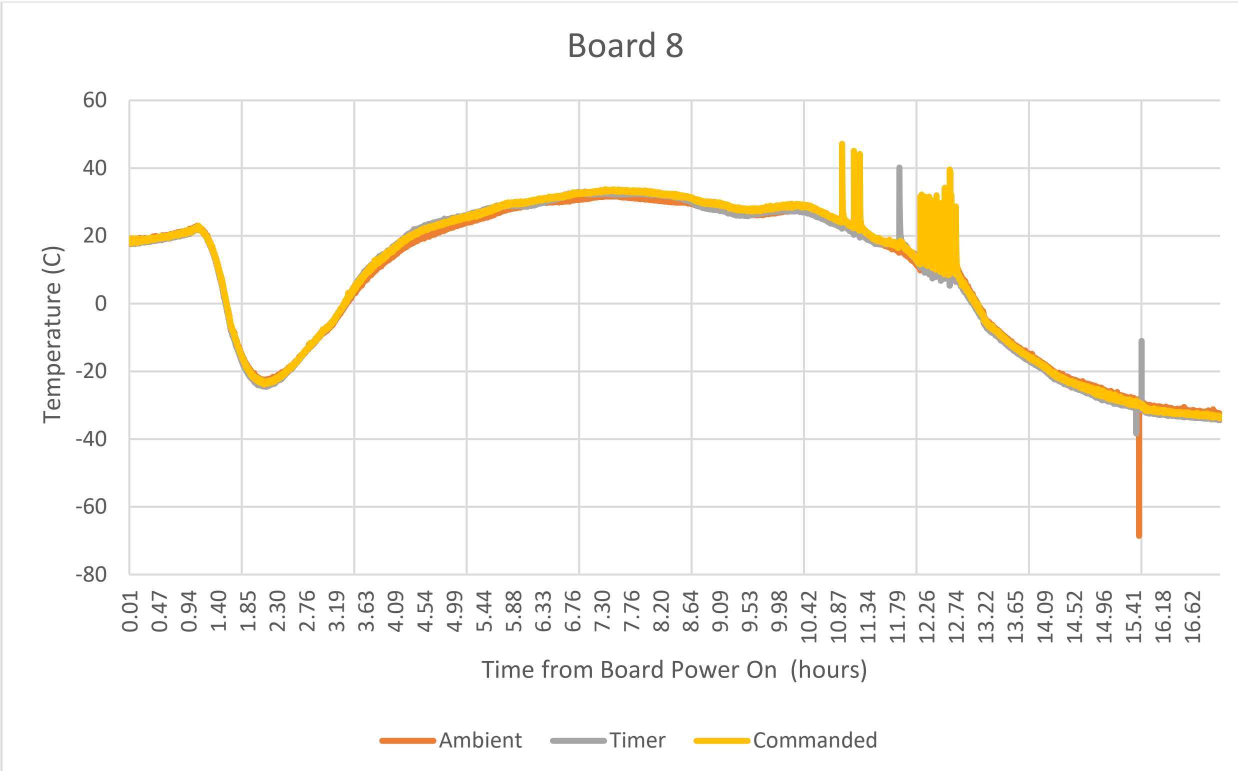


Figure 30: Board 8 temperature over the flight

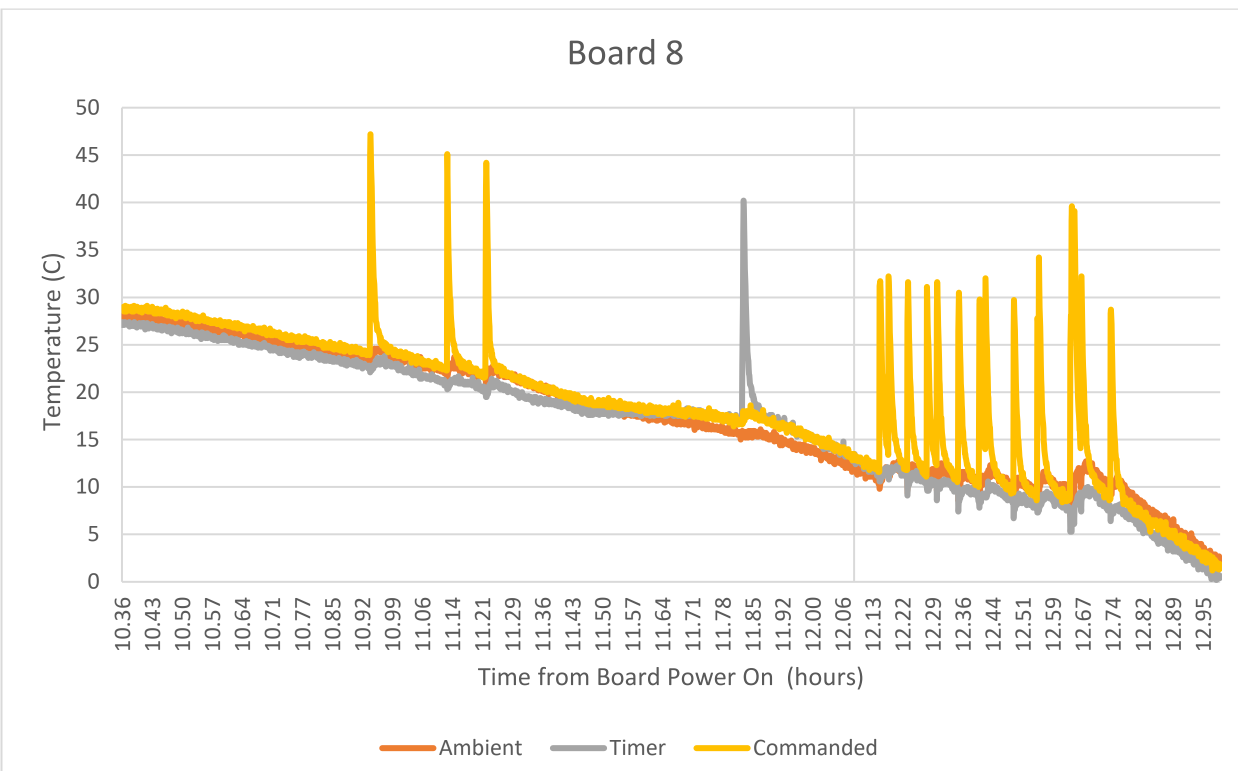


Figure 31: Board 8 temperature at time of interest

As can been seen in many of the zoomed in graphs there is often more than one spike in the commanded temperature data. In all the graphs, excluding the graphs for board 7 and 8, these multiple spikes are to be expected as the command was sent multiple times for additional testing and data. However, in the graphs for board 7 and 8 there are significantly more commanded temperature spikes than the other graphs. Some of these spikes are expected as the command was sent multiple times, but the command was not sent as many times as spikes can be seen. It is believed that this issue is a fault of the commanding. Boards 7 and 8 were on the same command and both boards exhibit the exact same behavior at the exact same time suggesting that the board were in fact receiving the command to cut. This was also the only command using the fourth bit (100), a bit that doesn't typically get high usage. The exact reason as to why the commands might have been repeatedly sent is unclear, but it is believed the issue is associated with this fourth-place bit. This is of course an important issue and will require further investigation but as it currently stands this bit will not be used for the NEBP and shouldn't pose any issue or additional risk to the success of the project and is only of concern of future work that may require the use of the bit (I.e., the need for more than four commands sent through the Iridium). It is very important to point out though that the boards did successfully cut at the correct time for the first commanded and timer side activation and even with this bizarre occurrence the flight would not have been jeopardized and would function like normal.

The finale bit of data collected from the flight was the observation of the strings under a microscope after the flight. These observations of the strings suggested that both the commanded and timer activated nichrome worked successfully.

Conclusion

Based on the findings presented above this new flight termination system has demonstrated a 100% success rate. The MSGC is confident this flight termination system will meet the requirements set by NASA and power the upcoming National Eclipse Ballooning Project.

Appendix A: Palestine Procedure

A. Date and Time of your arrival for integration:
    i. 7/26/10 at 3 pm CT
B. Approximate amount of time required for integration:
    i. 3 Hours
C. Name of the integration team leader: Lance Nichols
D. Email address of the integration team leader: lance.donald.nichols@gmail.com
E. List **ALL** integration participants (first and last names) who will be present for integration with their email addresses:
    i. Lance Nichols
        1. Email: lance.donald.nichols@gmail.com
    ii. Tim Uhlenbruck
        1. Email: t.uhlenbruck@yahoo.com
    iii. Randal Larimer
        1. Email: rlarimer@montana.edu
    iv. Michael Walach
        1. Email: michael.walach@montana.edu
F. Define a successful integration of your payload:
    i. Successful integration will be accomplished when the following criteria have been achieved:
        1. A location has been determined for each of the eight cutdown units that meets the following criteria:
            a. Mechanical signaling device visible to HASP camera.
            b. Location does not interfere with any other HASP payloads.
            c. Location allows for secure attachment to the HASP gondola.
        2. The main payload is deemed to be operational by meeting the following criteria:
            a. Payload is secured without any mechanical interferences.
            b. Payload is powered from HASP power.
            c. Payload interfaces with HASP serial connection and data is transmitted successfully.
        3. Commands can be sent to the payload by one of the following two methods:
            a. Iridium satellite network and modem are utilized.
            b. Commands are sent utilizing test switchboard utilizing a 5-wire interface.
        4. Environmental tests are passed by validating the following:
            a. If iridium antenna available and connected: iridium position is reported and received throughout the test. Position is reported if GPS is also available to the iridium.

b. Four cutdown units cut during the low temperature soak and this is signaled with the mechanical signal.
c. Four cutdown units cut during the high temperature soak and this is signaled with the mechanical signal.
d. Two units will cutdown using the timer nichrome at or near the low temperature soak this is signaled with the mechanical signal (exact timing of this may not result in soak time cutdown).
e. Two units will cutdown using the timer nichrome at or near the high temperature soak this is signaled with the mechanical signal (exact timing of this may not result in soak time cutdown).
f. Cutdown units that are not designated to trigger mechanical signals will still be fired at soak times with half of each timed and commanded instances happening at high and low, respectively (exact timing of this may not result in soak time cutdown).
g. Every instance of cutdown can be observed exclusively in the transmitted temperature data

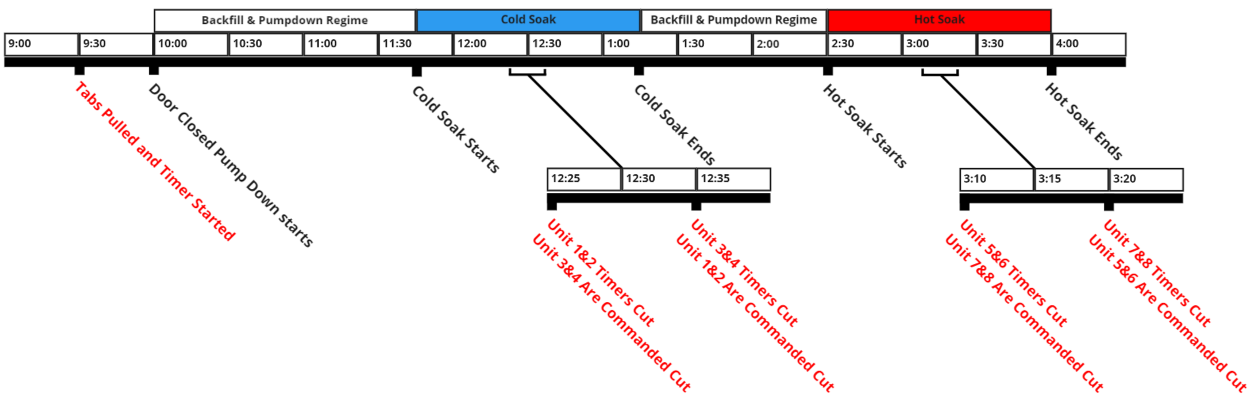
5. Cutdown validation
   a. Each unit's two cutdowns systems are validated each by one of any of the following three methods.
      i. Magnified inspection of the string shows melted strands consistent with hot nichrome cutting.
      ii. Temperature data indicating a temperature spike.
      iii. Mechanical indicator trips showing successful cutdown.

G. List all expected integration steps:
   i. Idle command sent, received, and latched by the OCCAMS unit.
      1. This step can be performed later if the Iridium network is not being utilized.
   ii. Set timed cutdowns based on suggested intervals provided by onsite personnel.
      1. The desired intervals are as follows:

Unit #	Timer Duration in hours
1	2:55
2	2:55
3	3:05
4	3:05
5	5:40
6	5:40
7	5:50
8	5:50

These intervals are subject to change based on suggestions provided on site.

iii. Run strings through cutdown units and mechanical triggers.
iv. Mount cutdown units to HASP Gondola.
v. Mount large payload plate to HASP Gondola.
vi. Pull tabs 30 minutes before payload enters the camber turning the cutdown units on.
vii. Start serial monitoring.
viii. Follow procedure outlined the timer plan (the specifics of this timing diagram are subject to change based on planned chamber timing).



1. Demonstrate ability to receive temperature data through serial interface.
2. Demonstrate ability to send commands to our payload through the iridium network.
    a. Desired Command Times

Unit #	T- Tab Pull Command Times in hours
1	3:05
2	3:05
9	2:55
4	2:55
5	5:50
6	5:50
7	5:40
8	5:40

These intervals are subject to change based on suggestions provided on site.

3. Demonstrate timed cutdown capabilities and confirm cutdown from timer.
4. Demonstrate system capabilities at extreme temperatures.

H. List all checks that will determine a successful integration:

i. Successful integration will be accomplished when the following criteria have been achieved:
    1. A location has been determined for each of the eight cutdown units that meets the following criteria:
        a. Mechanical signaling device visible to HASP camera.
        b. Location does not interfere with any other HASP payloads.
        c. Location allows for secure attachment to the HASP gondola.
    2. The main payload is deemed to be operational by meeting the following criteria:
        a. Payload is secured without any mechanical interferences.
        b. Payload is powered from HASP power.
        c. Payload interfaces with HASP serial connection and data is transmitted successfully.
    3. Commands can be sent to the payload by one of the following two methods:
        a. Iridium satellite network and modem are utilized.
        b. Commands are sent utilizing test switchboard utilizing a 5-wire interface.
    4. Environmental tests are passed by validating the following:
        a. If iridium antenna available and connected: iridium position is reported and received throughout the test.
        b. Four cutdown units cut during the low temperature soak and this is signaled with the mechanical signal.
        c. Four cutdown units cut during the high temperature soak and this is signaled with the mechanical signal.
        d. Two units will cutdown using the timer nichrome at or near the low temperature soak this is signaled with the mechanical signal (exact timing of this may not result in soak time cutdown).
        e. Two units will cutdown using the timer nichrome at or near the high temperature soak this is signaled with the mechanical signal (exact timing of this may not result in soak time cutdown).
        f. Cutdown units that are not designated to trigger mechanical signals will still be fired at soak times with half of each timed and commanded instances happening at high and low respectively (exact timing of this may not result in soak time cutdown).
        g. Every instance of cutdown can be observed exclusively in the transmitted temperature data
    5. Cutdown validation

a. Each unit's two cutdowns systems are validated each by one of any of the following three methods.
    i. Magnified inspection of the string shows melted strands consistent with hot nichrome cutting.
    ii. Temperature data indicating a temperature spike.
    iii. Mechanical indicator trips showing successful cutdown.

Appendix B: Fort Sumner Procedure

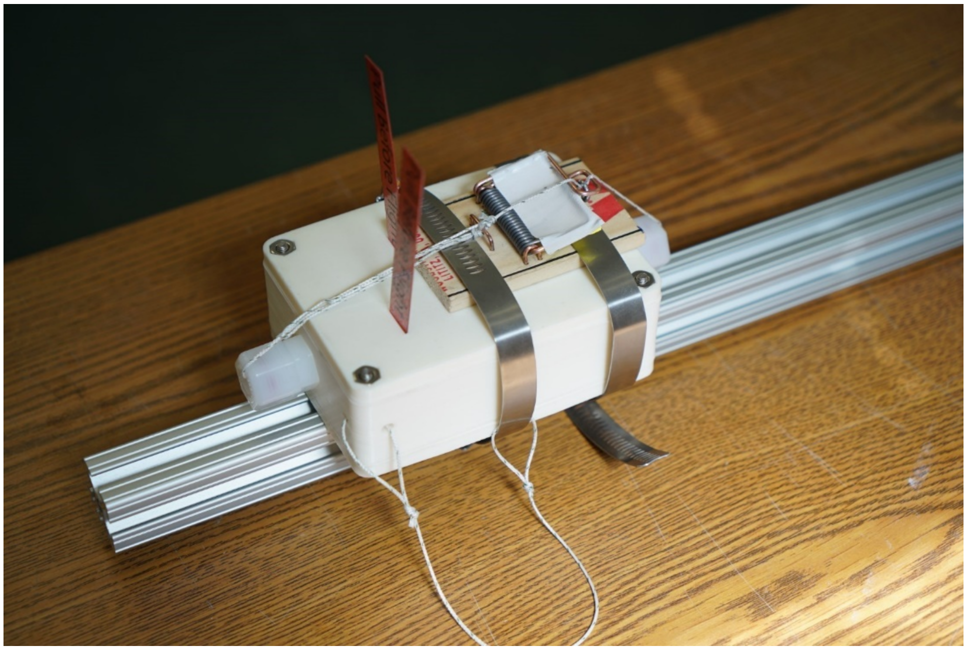
I. **Flight-line Setup & Pre-launch Checkout Procedures:**

A. **Flight-line Setup Period:** Provide a task list and timeline for the period leading up to the final HASP hang test and MRR. That is from about T = -7 days to about T = - 3 days. This is the period where you will have the greatest access to your payload and the most time available for setup activities. At the time of the MRR your payload should be ready for launch on a few hours notice and access to your payload will become limited.

- T = -7 to -4 Days: **Reprograming Timers** (Lance Nichols, Josh Phillips): Utilizing an msp430 development board and the Code Composer Studio software the timer controllers of each of the eight cutdown boards will be programmed to match the flight operation plan.
    - T = -7 to -4 Days: **Replace Batteries** (Lance Nichols, Tim Uhlenbruck): Remove existing AA batteries and replace them with new unexpired batteries (Energizer AA Lithium Battery, L91)
- T = -7 to -4 Days: **Retie String** (Lance Nichols, Tim Uhlenbruck): New string will be ran through all 8 cutdown units and tied over the mechanical signaling device utilizing a trucker's hitch.
- T = -7 to -4 Days: **Mount Cutdowns to Gondola** (Lance Nichols, Tim Uhlenbruck): The fully ready and primed 8 cutdown units will be remounted to the HASP gondola utilizing hose clamps.

B. **Pre-launch Checkout Period:** Provide a task list and timeline for the pre-launch period starting at T = -5 hours. Note that access to your payload after pickup (T = -4 hours) is **very** limited due to safety considerations. Thus, only very simple operations (e.g. flipping a switch, opening a valve) that can be performed external to your payload will be possible after HASP pickup.

    - T = -2 hours: **Remove Tabs** (HASP or CSBF personnel): From each the 8 cutdown units mounted to the HASP gondola quickly (this task should take no more than 1 minute) remove all 16 red tabs marked "PULL BEFORE FLIGHT" and report the time this task was completed with an accuracy of +- 1 minute to MSGC personnel before T = 0. When this is reported the 16 pull tabs are returned to MSGC personnel to demonstrate flight readiness.



II. Flight Operation Procedures

A. Uplink Command List: This list should contain all of the commands for your payload.

- Power On
  1. The name of the command.
     - i. Power On (HASP)
  2. The bytes (two) in hex format of the serial command.
     - i. This value is TBD
  3. A description of the command.
     - i. This command turns the payload plate on. This will allow downlink of data through HASP serial and turns on our Iridium Modem allowing us to send commands.
  4. Whether or not the command is critical to flight operations.
     - i. Yes turning on the device is critical
  5. A brief description of how it will be determined, from the ground, that the command was successfully executed.
     - i. The iridium modem on the payload will start to report to MSGC server this data is visible at our tracking website https://borealis.rci.montana.edu/tracking additionally, the serial stream of temperature data will begin.
  6. A contingency plan if the command is not successfully executed.
     - i. Send power off then repeat command (Turn it off and on again).
  7. The ramifications to flight success if a command is not executed properly.

i. Mission failure will be all but certain.

- Power Off
    1. The name of the command.
        i. Power Off (HASP)
    2. The bytes (two) in hex format of the serial command.
        i. This value is TBD
    3. A description of the command.
        i. It turns the payload plate off
    4. Whether or not the command is critical to flight operations.
        i. Powering down the device is only critical if a restart of our device is needed.
    5. A brief description of how it will be determined, from the ground, that the command was successfully executed.
        i. The Iridium Modem will no longer be reporting to the MSGC server, and the downlink serial will cease.
    6. A contingency plan if the command is not successfully executed.
        i. Send power on then repeat command (Turn it off and on again).
    7. The ramifications to flight success if a command is not executed properly.
        i. It is hard to determine the consequences of this command not working as its execution would only be mission critical if a problem has arisen that would include unforeseeable risk to mission success.

B. Commands to be executed during climb-out: The "Power On" command should be sent at T= 0 or even earlier if possible at T= -2

C. Flight Configuration Setup: No commands will be sent through HASP during nominal operation.

1. The following commands will be sent through the iridium command center:

Iridium Command ID	Time of command in hours
001	T = 4
010	T = 6
011	T = 8
100	T = 10

D. Failure Response:

Event	Method to Determine Event	Method to Correct Event
Serial data stops	No data has been received in 10 minutes.	Turn it on and off again
Iridium data stops	No data has been received in 10 minutes.	Turn it on and off again
All data stops	No data has been received in 10 minutes.	Turn it on and off again

E. Termination: None.

Appendix C: Student Team Demographic

Name	Start Date	End Date	Role	Student Status	Race	Ethnicity	Gender	Disabled
Lance Nichols	1/2/21	Present	Project Manager	Undergrad	White		Male	No
Tim Uhlenbruck	1/2/21	Present	Mechanical Lead	Undergrad	White		Male	No
Andy Kirby	1/2/21	5/1/21	Electrical Lead	Undergrad	White		Male	No
Josh Phillips	5/3/21	10/29/21	Mechanical/ Programming	Undergrad	White		Male	No

Andy Kirby graduated in May of 2021 and is now working for Los Alamos National Lab. The rest of the student team are in their final year of school and will graduate in May 2022.

Appendix D: Articles, Presentations and Awards

- This project is a part of the Nation Eclipse Ballooning Project which was recently awarded 6.5 million dollars from NASA
- https://www.nasa.gov/feature/wallops/2021/student-experiments-float-over-new-mexico
- https://www.nasa.gov/wallops/2021/feature/fall-2021-hasp-balloon-mission-will-fly-11-student-payloads
- The predecessor to this termination system was presented at AHAC 2020
- This project was used as a Senior Design project and was presented at Montana State Universities design fair in December of 2021. The poster from the presentation is below

Flight Termination System for the 2024 NASA National Eclipse Ballooning Project

By: Lance Nichols (ME) & Tim Uhlenbruck (ME)

Intro

This project sought to develop and test an inline flight termination system with redundent features to meet the requirements set by NASA. The High Altitude Student Platform (HASP) was utilized as a testing bed to verify the validity of this termination system.

Hardware

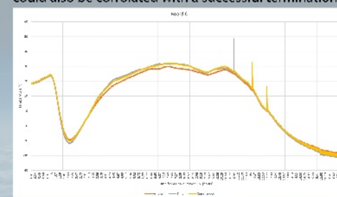
The termination system consists of two main parts, a 3D printed waterproof enclosure and PCB. The enclosure consists of three parts printed out of ASA and utilizes silicone O-rings and compression fittings to remain waterproof during all flight conditions. The PCB has two seperate but nearly identical circuits. Both circuits are powered by a AA battery and use a MOSFET to power a hot nichrome wire to cut the flight line terminating the flight. The difference between the two circuits is how the MOSFET is activated to cut the line. One circuit is controlled by an XBee3 radio/microcontroller combo unit that can receive a command on a local radio network to terminate the flight. This local network can receive commands from the Iridium satellite network. The other circuit is controlled via a MSP430 that acts as a timer. The flight will be terminated when the timer runs out and can be set to any length of time as needed for flight operations.

Testing

The initial testing was conducted at the BOREALIS lab in Bozeman. This was primarily testing of different nichrome wire gauges, long duration freezer tests and actual balloon flights. The nichrome testing found that the 30 AWG wire was the best choice of wire gauge and was used for all future testing and flights. The freezer tests led us to discover that these boards had a useful battery life of about 16 hours for the radio commanded side and the timer side lasted over a week. We stopped the test after a week as the units only need to operate from 4-8 hours at a time. It was also found in these tests that after 10-16 hours at $-20\,^{\circ}C$ the radio side would often brownout after receiving the command to terminate flight. While the line would still always cut, these conditions are very unlikely to occur in a flight, the reseting of the device due to the brownout was still undesirable. This led to changing how the MOSFET fired. The MOSFET was switched from being activated for 10 seconds straight to a 30% duty cycle of on and off for 10 seconds. This termination unit was flown on a balloon flight multiple times with successful operation each time. The next round of testing was conducted in Palestine, TX at NASA's ballooning facility. We utilized their thermal vaccuum chamber to conduct multiple long duration tests in extreme enviroments even beyond that of a flight. Tests were ran at -60 and 60 $^{\circ}C$ while at atmospheric pressures found at 120,000ft. From this it was found that a duty cycle of 30% was not sufficient in these extreme low temperatures and the switch to a 70% duty cycle was made.

NASA Test Flight

The final component of testing was to fly 8 units on NASA's HASP flight in Fort Sumner, NM. The 8 units flew attached to the side of the NASA platform. Live video and temperature data was streamed through NASA's ground link to monitor the units during the entire flight. The live video allowed vision of a mechanical flag triggered after a successful cut providing live feedback of sucsess. A spike in the temperature data could also be corrolated with a successful termination.



Conclusion

This system has proven it is reliable and holds a 100% success rate for flight termination. It meets all the NASA requirements and will be used for the 2024 NEBP

Acknowledgements

Randy Larimer - PE
Dr. Michael Walach
MSGC - BOREALIS
NASA and HASP