McNair Scholars Research Journal

Volume 5 Article 6

2018

An Investigation of the System Architecture of High Power Density 3U CubeSats Capable of Supporting High Impulse Missions

Naia I. Butler-Craig
Embry-Riddle Aeronautical University

An Investigation of the System Architecture of High Power Density 3U CubeSats Capable of Supporting High Impulse Missions

Naia I. Butler-Craig,[1]
Embry-Riddle Aeronautical University, Daytona Beach, FL, 32114, United States

This study examines the system architecture of high power density 3U CubeSats capable of supporting high impulse missions. Under analysis is the ALBus CubeSat, a 3U High Power Density CubeSat at the National Aeronautics and Space Administration's Glenn Research Center in Cleveland, Ohio. The mission is a technology demonstration of a 100-Watt power management and distribution system aboard a small volume CubeSat and serves as evidence of CubeSats being able to provide high power to the subsystems necessary to support high impulse missions. This study mainly explores the thermal behavior of a CubeSat subjected to substantial waste heat due to extra power generation. It was found through a thermal vacuum test that, despite 100-Watts of waste heat being deposited into the system, the thermal limits of the electrical components were not exceeded and remained at steady-state operable temperatures. The thermal vacuum test proved the ALBus CubeSat was able to provide enough power without overheating to the point of detriment to its electrical components. A propulsion system is a fundamental necessity for any high impulse mission so a practical option for 3U CubeSats was explored to solidify the viability of such a spacecraft. The Miniature Xenon Ion Thruster, or MiXI, being researched and developed at NASA's Jet Propulsion Laboratory, is proven to be a desirable propulsion system for small satellites due to its high efficiency, low contamination, and precise thrust and impulse bits. It also is only 3 inches in diameter and can be operated on less than 100-Watts of power. This study is intended to help solidify the feasibility assessment of a high-power density CubeSat capable high-impulse missions.

.

I. Nomenclature

c	=	specific heat
m	=	mass
Q	=	heat
T	=	temperature
J	=	Joules
s	=	seconds
W	=	Watts

II. Introduction

CubeSats, having recently emerged upon the aerospace industry, are revolutionizing the future of spaceflight. Their relatively tiny volumes compared to larger, conventional satellites, make them time and cost-efficient spacecraft to develop, procure and/or fabricate as well as launch. As they grow in ubiquity and continue to progress and evolve, and as other spacecraft subsystems, like thrusters, and power systems continue to shrink in size, CubeSats prove their capability to support missions with high-ΔV. ΔV (pronounced delta-vee) is defined as the impulse required to perform a maneuver. The ability to produce enough ΔV is one of the limiting factors of CubeSats at its current stage in

[1] Student, Embry-Riddle Aeronautical University

development. Their small size poses strict constraints on payload, propulsion, and other subsystem volumes. To support any mission that requires orbit transfers, or any action where propulsion is needed, there will be a tradeoff between, propellant and payload space. Higher ΔV missions require more propellant thus resulting in less space for any scientific payload or instrument meant to fly on board the CubeSat. The lack of space in the CubeSat also restricts its ability of sustaining vital subsystems that CubeSats need to perform a complex mission. For an example, battery packs have the potential to take up 1U, 1 cube with dimensions of 10 x 10 x 10 cm., of the CubeSat volume or more which severely limits the available volume. Another constraint imposed by the small volumes of CubeSats is power generation.

As mentioned before, CubeSats come in multiples of the standard U. U stands for unit which is equivalent to a 10 x 10 x 10 cm. (roughly 4 x 4 x 4 in.) cube. Many researchers are using microsatellites to perform planetary science, biological and numerous multidisciplinary research missions. However, the scope of the abilities or data that can be obtained are very limited due to the lack of power generation, a propulsion system for on orbit maneuvering, and robust attitude determination and control systems. Such CubeSats either fly on sounding rockets, that do not breach Earth's atmosphere in a suborbital flight, or Low-Earth Orbit (LEO). An example of these recent flying CubeSats include the atmospheric science microsatellite, DICE (October 2011)[2] and the magnetospheric science CubeSat, Cinema 1 (September 2012)[3]. The proposed CubeSats discussed in this study are intended for missions that require more complex orbit trajectories.

A study carried out by researchers at the University of California, Los Angeles (UCLA) investigated the use of a 3U CubeSat, that is loosely based on the ELFIN CubeSat under development at UCLA[4], with a mini ion thruster to execute a lunar mission. The study utilizes the results from the first-order design process to design the theoretical Lunar Mission, or LuMi, CubeSat[5]. The study explores the specific power, mass, and volume budgets based on the mission to reach the Lunar surface from LEO. The mini propulsion system used is the Mini Xenon Ion (MiXI) thruster being developed by UCLA and NASA's Jet Propulsion Laboratory (JPL)[6]. This thruster can operate on less than 100 W, while maintaining the high specific impulse of large-scale ion thrusters which makes it a very desirable option for miniature satellite applications. The lunar mission CubeSat and mission capability assessment carried out by Conversano[7], and Wirz[8] demonstrate that CubeSats can carry out high-ΔV missions using miniature thruster technology.

What this study aims to accomplish is demonstration of the feasibility of such a CubeSat considering the high power being generated by the spacecraft. High waste heat is expected to be deposited into the spacecraft in response to the high power being generated and charged to the payload and other necessary subsystems. The objective of this investigation is to ensure that the internal components of said spacecraft will not overheat due to the waste heat in the system.

The Advanced Electrical Bus (ALBus) CubeSat is a CubeSat developed by the National Administration of Aeronautics and Astronautics (NASA) Glenn Research Center serving as a technology demonstration of 100 Watt-power management and distribution (PMAD), and resettable shape memory alloy deployable solar array technologies. ALBus CubeSat will be under investigation to prove that CubeSat's are capable of high power densities and adequately control the waste heat subsequently generated therein. The system architecture of the ALBus CubeSat will be investigated to assess how the strategic spacing of, and strategically placed contact points between subsystems contributes to the thermal control of the spacecraft. It is a desirable spacecraft to investigate due to its ability to effectively generate and discharge 100 W of power to the discharge board that is representative of a high-power payload. This is necessary because the high-power payload can be substituted for a thruster, attitude determination

[2] Crowley, Geoff, et al. "Dynamic ionosphere CubeSat experiment (dice)." (2011).
[3] Lin, R. P., et al. "Cinema (cubesat for ion, neutral, electron, magnetic fields)." *AGU Fall Meeting Abstracts*. 2009.
[4] Caron, R. "ELFIN Engineering Overview.". Institute for Geophysics and Planetary Physics, University of California, Los Angeles, 2010 *(unpublished)*.
[5] Conversano, Ryan, and Richard Wirz. "CubeSat lunar mission using a miniature ion thruster." *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2011.
[6] Conversano, Ryan W., and Richard E. Wirz. "Mission capability assessment of CubeSats using a miniature ion thruster." *Journal of Spacecraft and Rockets* 50.5 (2013): 1035-1046.
[7] Graduate Student, Department of Mechanical and Aerospace Engineering, UCLA
[8] Assistant Professor, Department of Mechanical and Aerospace Engineering, UCLA

and control system (ADCS), and/or a payload specific to whatever science mission is being executed, should they all be able to operate on less than 100 W combined.

These are all relevant aspects to the research question because in order for CubeSats to be used for greater purposes, they require these basic subsystems. For an example, an attitude determination and control system is necessary for the propulsion and communications components on board the CubeSat since it allows for attitude control and stabilization on all 3 axes. For many instrument demonstrations involving CubeSats, being able to point a component (e.g. antenna, probe etc.) is vital to the instruments capability to function effectively if not at all. Propulsion systems are also important for orbital maintenance on CubeSat missions that involve transcending beyond Low-Earth Orbit (LEO). High frequency communications systems are another important subsystem for CubeSat missions that involve a great deal of data. It is imperative that CubeSats can generate enough power for these subsystems for future payload applications.

Since the propulsion system is one of the most if not the most vital subsystem for high impulse missions, a specific thruster is also briefly explored within this study. This investigation explores that of xenon ion propulsion due to its high impulse and efficiency capabilities. There also have been successful efforts in the miniaturization of xenon ion thrusters which also contribute to why it is a desirable option for CubeSats. In addition to providing (1) high specific impulse, *Isp*, (~1000 – 3000 s), these thrusters can provide (2) very precise thrust and impulse bits, (3) low disturbance thrust, and (4) low contamination and spacecraft interaction potential. These capabilities are attractive for high ΔV exploration and orbit/inclination change missions, precision orbit maintenance, formation flying, or precision pointing/control.[9]

III. Research Method

The methods or steps taken to perform the research involved analysis of the ALBus CubeSat. First, a test CubeSat was assembled to mimic the flight hardware (as the flight hardware was not used for experimentation), utilizing engineering development unit (EDU) printed circuit boards (PCBs). EDU versions of the other hardware in the spacecraft, such as the retention and release mechanism (R&R) and the battery pack, were also used. All the strategically placed thermal conductivity points and spacing between the boards were replicated in the test CubeSat to ensure the accuracy of the thermal behavior compared to that of the flight hardware. A thermal vacuum test was performed on the test satellite to observe how the internal electrical components reacted to the expected on-orbit orbital environments and waste heat generation. Finally, the data was recorded and analyzed to first, verify 100 W of waste heat was actually deposited into the system, and two, the electrical components remained at steady-state operable temperatures based on their respective temperature limits.

IV.Deconstructing the ALBus CubeSat

As mentioned before, The Advanced Electrical Bus (ALBus) CubeSat will demonstrate the performance of a 100 W capable power management and distribution (PMAD) system. The CubeSat will charge batteries to a desired state of charge utilizing a maximum power point tracking algorithm and discharge a maximum of 100 Watts of power to a target load representative of a high-power payload. The technology demonstration will prove the designs work in an on-orbit environment for follow on missions requiring high power density operations.[10]

The target load in the ALBus CubeSat spacecraft is a bank of resistors that will radiate the 100 Watts of waste heat directly to the passive thermal control system. The CubeSats thermal control system is an aluminum heat sink, or an aluminum block of metal, that absorbs the heat from the discharge board via thermal conduction and expels the heat to the environment via radiation. The ALBus CubeSat was designed in such a way to support this flow of energy to

[9] Wirz, R. E. "Miniature ion thrusters: A review of modern technologies and mission capabilities." *Proc. 30th Int. Symp. Space Technol. Sci.*. 2015.
[10] Heidman, Kelly, and Heather O'Dell. "ALBus CubeSat Will Demonstrate Power Technology."*NASA*, NASA, 17 July 2017, www.nasa.gov/image-feature/albus-cubesat-will-demonstrate-power-technology.

the heat sink and keep the electronics power system circuit boards, and other subsystems, at a steady-state operable temperature. The thermal vacuum test was performed to validate this thermal model.

The ALBus CubeSat demonstrates a small satellite's capability of providing 100 Watts of power to a high-power payload with a power requirement of 100 Watts. This is evidence of its capability to support multiple subsystems where the summation of the respective power requirements is less than or equal to 100 Watts.

A. System Architecture

The ALBus CubeSat is a 3U CubeSat meeting all dimensional specifications and requirements outlined in the CubeSat design specifications document.[11]

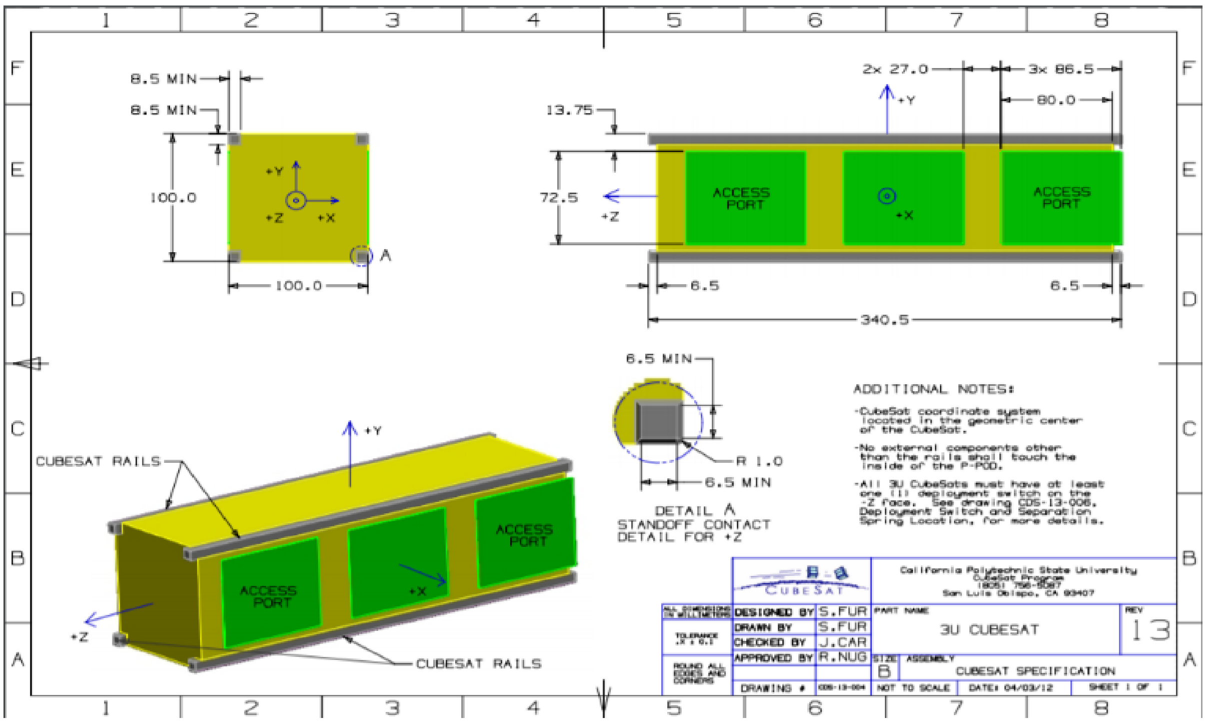

Fig. 1 3U CubeSat Design Specification Drawing

It fits the standard 3U CubeSat dimensions and the only "payload" it supports is the discharge board which is fastened to the aluminum Heat Sink (thermal control system). The chassis is the structural frame housing the internal components of the CubeSat. The end of the chassis closes to the Heat Sink houses the deployable solar arrays that are mounted by Shape Memory Alloy (SMA) hinges that deploy when exposed to certain temperatures. Shape Memory Alloys are an alloy that remember its original shape and can return to it after being deformed when heated. The electronics stack, or PCB stack on the inside of the chassis, was designed keeping the thermal limits of each circuit board in mind (**Table 1**). The stack up includes the Charging Board, battery pack and bracket, the Processor Board, Auxiliary Board, the retention and release mechanism and the Lithium-1 Radio Board in that order. The system architecture is strategically designed to provide thermal conductivity interfaces where needed. The best example of this is the Heat Sink and discharge board. The discharge board is fastened to the Heat Sink providing direct and flush contact so that most of the waste heat flows in the direction of the Heat Sink as opposed to the charging board, that is directly under the Discharge Board. The spacing between the boards is also a strategic way of thermally isolating them from each other to ensure reasonable heat transfer between the different subsystems. For example, the most thermally isolated component of the internal stack is the battery pack. Since it is intended to be operating for the duration of the CubeSat's life, they have very strict temperature limits, that if exceeded will permanently damage the performance of the rest of the system. Body mounted solar arrays are mounted to each external face of the CubeSat chassis which is

[11] Mehrparvar, Arash, et al. "CubeSat Design Specification Rev 13." The CubeSat Program, Cal Poly San Luis Obispo, US (2014).

important to note when considering the thermal characteristics of the system. With body mounted solar arrays occupying all the external faces, the CubeSat is considered a closed volume meaning less heat can escape the system. A model is provided in Fig. 2 showing the internal components of the ALBus CubeSat.[12]

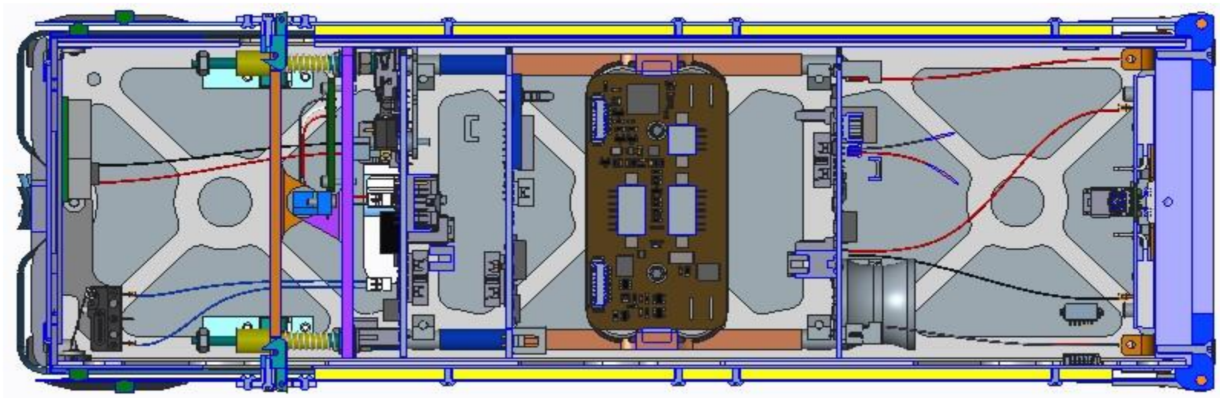

Fig. 2 CREO Model of Interior of ALBus CubeSat (Photo from Thermal Vacuum Test Plan)

Fig. 3 provides a depiction of the PCB stack up with labels describing each of the internal components within the chassis of the ALBus CubeSat.[13]

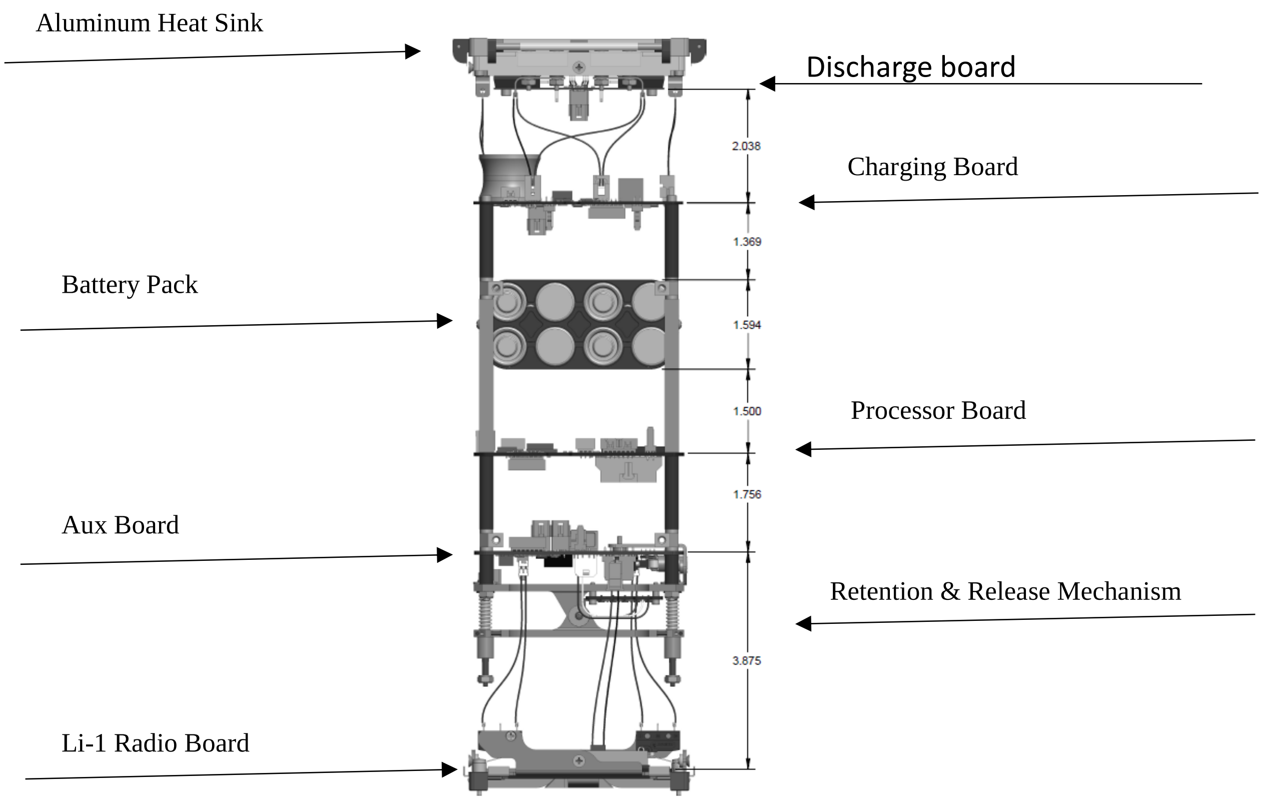

Fig. 3 PCB Stack Up by NASA ALBus CubeSat Team

[12] ALBus CubeSat Thermal Vacuum Test Plan (*unpublished*).
[13] CAD Model of PCB Stack up provided by ALBus CubeSat Team (*unpublished*).

V. Testing

The objectives of the thermal vacuum test were to prove 100 W of waste heat was deposited in the system and show the rest of the hardware did not exceed their temperature limits. First, the test CubeSat was heavily instrumented with type T thermocouples and hooked up to the calibrated data acquisition system (DAQ) provided by the testing facility. The thermal vacuum chamber used is located in NASA Glenn's Testing Facility and is called VF-10. Inside, it has a thermal shroud populated with patch heaters that are turned on to increase the temperature in the chamber for hot temperature set points. For cold temperature set points, the chamber is cryogenically cooled using Liquid Nitrogen (LN_2). The thermal shroud was also instrumented with thermocouples.

The ALBus CubeSat was placed in the thermal vacuum chamber and was pumped down to less than 10^{-4} Torr of pressure to simulate the orbital environment. The test temperature set points were derived from thermal modeling of the CubeSat's expected orbital environment based on its orbital trajectory. They were used to create the test profile (**Fig. 4**). The test is split up into two sections, the cold and hot dwells. The word dwell is used here to describe the duration of time, 1 hour, that the CubeSat hardware will be held at each temperature set point. The cold dwell temperature set point chosen was -10°C as that is the lowest temperature the CubeSat is expected to be exposed to during its orbital life. The hot dwell temperature is a little above ambient, 35°C, and is also the highest temperature expected on orbit. Since the objective of the CubeSat's operational mission is to provide 100 W of power to a target load, that function is tested during each dwell. The way in which it is tested is through the 100 W load, or discharge board, manually being turned on in each dwell. This is simulated by turning on the patch heaters taped to the top of the discharge board.

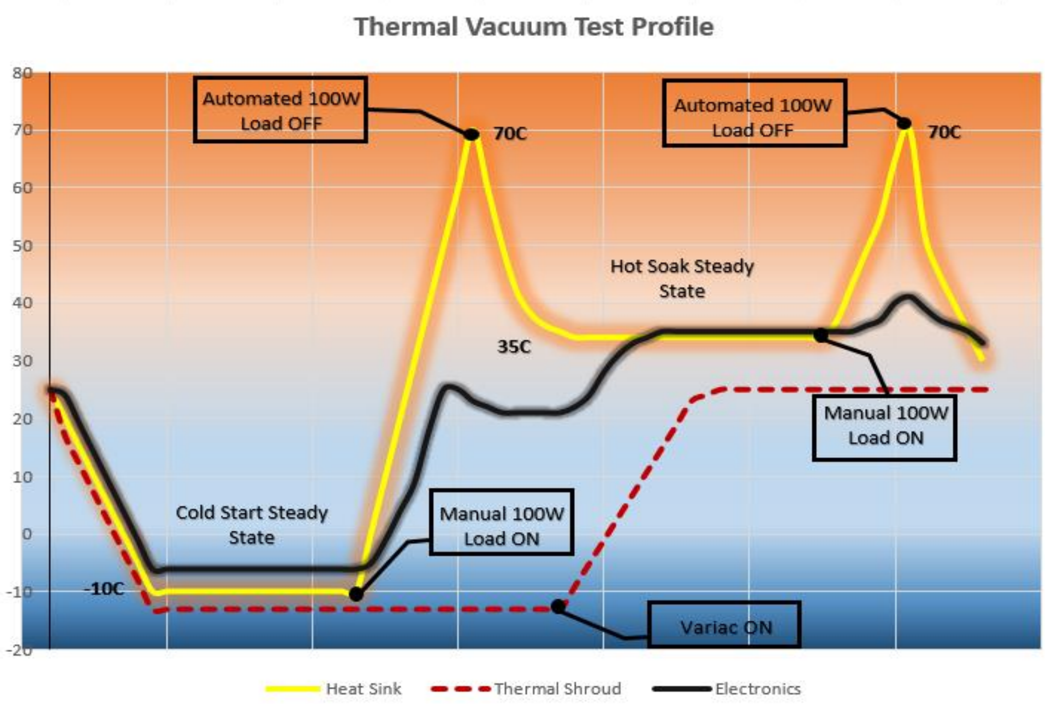

Fig. 4 Thermal Vacuum Test Profile

The test profile above walks you through how the test is conducted. After the pressure in the chamber reaches a hard vacuum, the test begins at an ambient, room temperature. The thermal shroud is set to the cold dwell temperature, and the 100-Watt load is manually turned on, the Heat Sink is allowed to reach its temperature limit of 70°C, then automatically shut off via the flight test software. The 70°C limit for the heat sink is derived from theoretical calculations from the thermal model that proved 100 Watts of heat was reached by the Heat Sink at 70°C if the initial temperature was ambient. The temperatures are allowed to naturally steady back out to an ambient temperature, before the same steps are carried out at the hot dwell temperature set point. This data was tracked on the DAQ that is connected to a breakout board in which the leads of the thermocouples were plugged. The DAQ plotted the temperature readings against time at various sampling rates.

A. Analytical Techniques

This tests objective is to verify that 100 W of power was discharged to a target high power payload, or the discharge board, and to validate the thermal analysis that showed the CubeSat would be thermally controlled within the temperature limits of the different electronics therein.

The first objective was validated by calculations from the test that prove 100 Watts of waste heat was delivered to the Heat Sink via the discharge board. In order to calculate that waste heat, a MATLAB algorithm (**Fig. 4**) that processed the data by calculating the run time of the 100W Watt load (the discharge board) which was used in the specific heat formula (**Eqn. 1**), where mass, *m*, is in grams, specific heat, *c*, is in Joules per gram per Kelvin, temperature, *T*, is in degrees Celsius and Heat, *Q*, is in Joules.

$$\boldsymbol{Q = mc\Delta T} \qquad \textit{Eq. (1)}$$

To find the amount of waste heat in Watts, that the Heat Sink absorbed the following equation (**Eqn.** 2) was used where *J* is Joules, *W* is Watts and, *s* is seconds.

$$\boldsymbol{J = W * s} \qquad \textit{Eq. (1)}$$

The second objective was validated by the test showing that despite the amount of waste heat generated in the small volume of the 3U CubeSat, the rest of the electrical subsystem components did not exceed their operational functional limits. The circuit boards utilized were standard thus their temperature limits fall within the ranges found in **Table 1**.

Operational Temperature Limits of Various Subsystem Components

Subsystem Component	Operational Temperature Limits (°C)
Electronics Boards (Processor, Aux etc.)	-40 < T < 70
Radio	-40 < T < 70
Solar Panels	-50 < T < 50
Li-Ion Batteries	-5 < T < 45

Table 1 Thermal limitations of various Subsystem Components[14]

VI. Results

A. Thermal

As stated before, one of the objectives of the thermal vacuum test was to validate a thermal model in which the CubeSat subsystem components maintained a steady-state operable temperature despite the 100 W of waste heat being deposited into the small, closed volume of the CubeSat. Referencing the thermal operational limits described for each subsystem component in **Table 1**, any temperature between -40C and 70C that is consistently held during the 100-Watt discharge portion of the dwell is considered a steady-state operational temperature.

[14] ALBus CubeSat Thermal Analysis Document (*unpublished*)

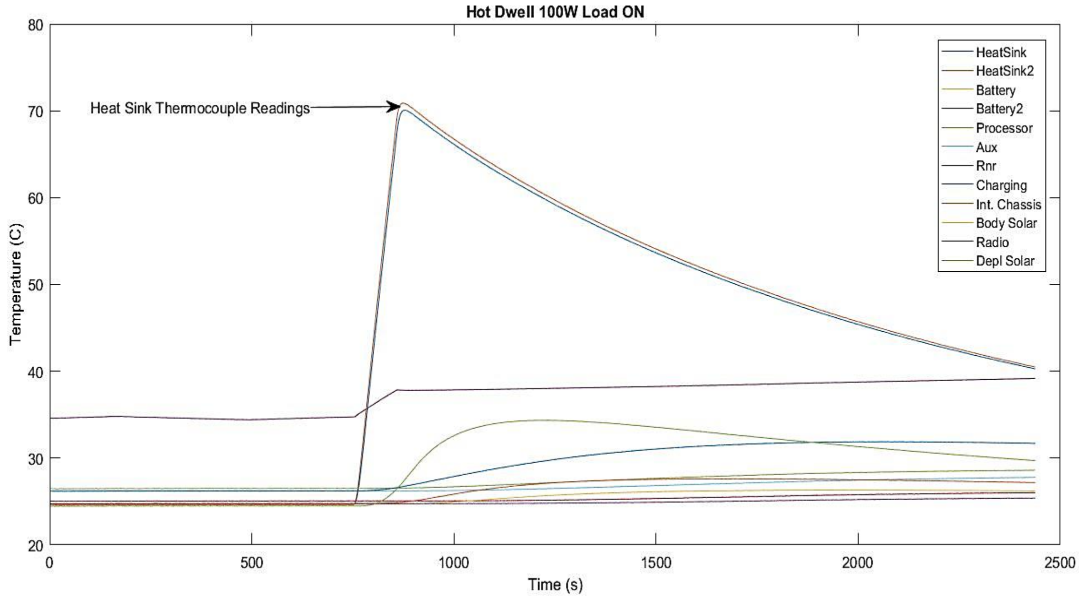

Fig. 5 MATLAB plot of Data from Hot Dwell 100W Load ON portion of Thermal Vacuum test

For the hot dwell portion of the Thermal Vacuum test, the thermal data collected show the expected rise in temperature of the Heat Sink thermocouples. Considering the system architecture, in which the 100-Watt load discharge board is fastened to the Heat Sink, that spike in temperature is expected. The rest of the CubeSat hardware remained within 25°C-30°C range. According to the plot, the temperature of the subsystem components, outside of the Heat Sink, slightly increased and then maintained a steady-state. Some components, like the processor, charging board and battery pack, increased more than others at the start of the 100-Watt discharge. However, this was expected due to their placement with respect to the Heat Sink. It is important to consider the waste heat being produced by the batteries. During nominal operations, the thermal model predicted about 0.5 Watts of waste heat emissions from the battery pack. However, during the 100-Watt discharge, 6 Watts of waste heat is expected which also explain the small jump in temperature seen in the plot.

B. Power

The other objective of the Thermal Vacuum test was to confirm that 100 Watts of power was provided to the discharge board. Successful discharge of 100 Watts to the discharge board is shown through calculations that show the Heat Sink absorbed 100 Watts of waste heat. This was calculated using the MATLAB algorithm in **Fig. 4**. The results are below (**Table 2**).

MATLAB Processed Hot Dwell Data

Variable	Value
Heat Sink Max Temperature (C)	70.066
100W Load ON Run Time (s)	109
100W Load ON Run Time (min)	1.817
Heat Sink Weight (g)	265
Specific Heat of Aluminum (J/g·K)	0.9
ΔT of Heat Sink (C)	45.43
Heat Absorbed (W)	99.53

Table 2 Calculations from MATLAB algorithm to determine amount of heat absorbed by the Heat Sink.

VII. Discussion

This study was conducted to assess the feasibility and investigate the system architecture of a high-power density CubeSat. If CubeSats are to be used for complex, high impulse missions, being able to provide enough power for the necessary subsystems to execute the mission is imperative.

The approach to proving the feasibility of a such a CubeSat was to perform a Thermal Vacuum test that would yield data proving that 100 Watts of waste heat was provided to a high-power payload. The high-power payload in the CubeSat is a discharge board containing a bank of resistors. The power is converted into waste heat by the bank of resistors and is absorbed by the Heat Sink via thermal conduction. The amount of heat absorbed by the Heat Sink in Watts is equal to the amount of power that was provided to the discharge board. The rational for conducting and analyzing the test this way is due to the system architecture of the CubeSat. The architecture supports heat flow in the direction to the Heat Sink from the discharge board by providing a flush interface between the two with a large enough surface area.

This is important when considering the thermal control of the nanosatellite. A major issue when dealing with high-power density spacecraft is thermal control. There needs to be some version of expulsion, absorption, or utilization of the waste heat that is subsequently deposited into the system. With micro spacecraft, the small volume intensifies the challenge of adequate thermal control of the spacecraft. Thermal control is a highly significant aspect of spacecraft system design since excessive heat has the potential to damage the hardware therein thus jeopardizing the spacecrafts operational ability. The thermal control system of the CubeSat is also examined through the Thermal Vacuum test to show that despite the high-power generation, the rest of the system is kept at steady-state operable temperatures. One discrepancy that arises when using the CubeSat as an example of high-power density nanosatellites thermal control is the impracticality of a spacecraft intentionally generating 100 Watts of waste heat. The discharge board would be considered an extremely inefficient payload. The amount of waste heat is dependent upon the efficiencies of the power consuming subsystems. 100 Watts may be considered an excessive amount of waste heat in such a small volume spacecraft.

The data derived from the Thermal Vacuum test was successful in proving the CubeSat's capability of providing 100 Watts of power to a high-power payload. The specific heat equation (**Equation 1**) was used to calculate the total Watts absorbed by the 265g aluminum Heat Sink which was found to be 99.5 W and is within 0.5% percent error. This error is relative to the theoretical 100 W expected to be generated. This therefore verifies that 100 W of waste heat was, indeed, present in the system after the discharge.

The data from this test also the rest of the hardware is controlled at a steady-state operable temperature between 25ºC-30ºC which are well within the temperature limits of the electrical components found in **Table 2**.

As stated before, if CubeSats are to be utilized for high impulse, or ΔV, missions, they will need to be able to support a propulsion system. Since a high-power density CubeSat is concluded to feasible, various propulsion options can be explored.

C. Propulsion

The presence of xenon ion propulsion is increasing in the aerospace industry due to the high efficiencies and propellant mass savings it offers in comparison to chemical propulsion. The miniaturization of this technology has made it a very desirable option for CubeSats.

Miniature, or micro, ion thrusters with diameters $\leq$ ~3 cm, have increased the capabilities and science return that can be delivered by microsatellites since they can deliver desirable thrust levels of up to about 1-2 mN, thrust control, propellant efficiency (Isp ~1000 – 3000 s), and mission ΔV. Their precise and high impulse bits, low disturbance thrust, and low contamination and spacecraft interaction potential make them applicable to a wide range of missions. CubeSats using the miniature xenon ion, or MiXI, (**Fig. 7**) thruster being developed by NASA's Jet Propulsion Lab, have already been researched through mission capability assessments for lunar missions. [15]

[15] 9

Fig. 6 Mini Xenon Ion (MiXI) Thruster (3cm diameter).

With power budgets in consideration, another attractive characteristic of the MiXI thruster and its integration to nanosatellites is the relatively low power budget. MiXI thrusters can be operated anywhere between 20-60 Watts with proven efficiencies up to 56%. It also important to remember that not all subsystems need to operate simultaneously. The use of duty cycles during the mission life of a CubeSat further supports the concept of using them for more complex missions. Being able to manage and distribute 100 Watts of power to a payload, gimbal system, and thruster is more than enough to operate over the life cycle of a mission.

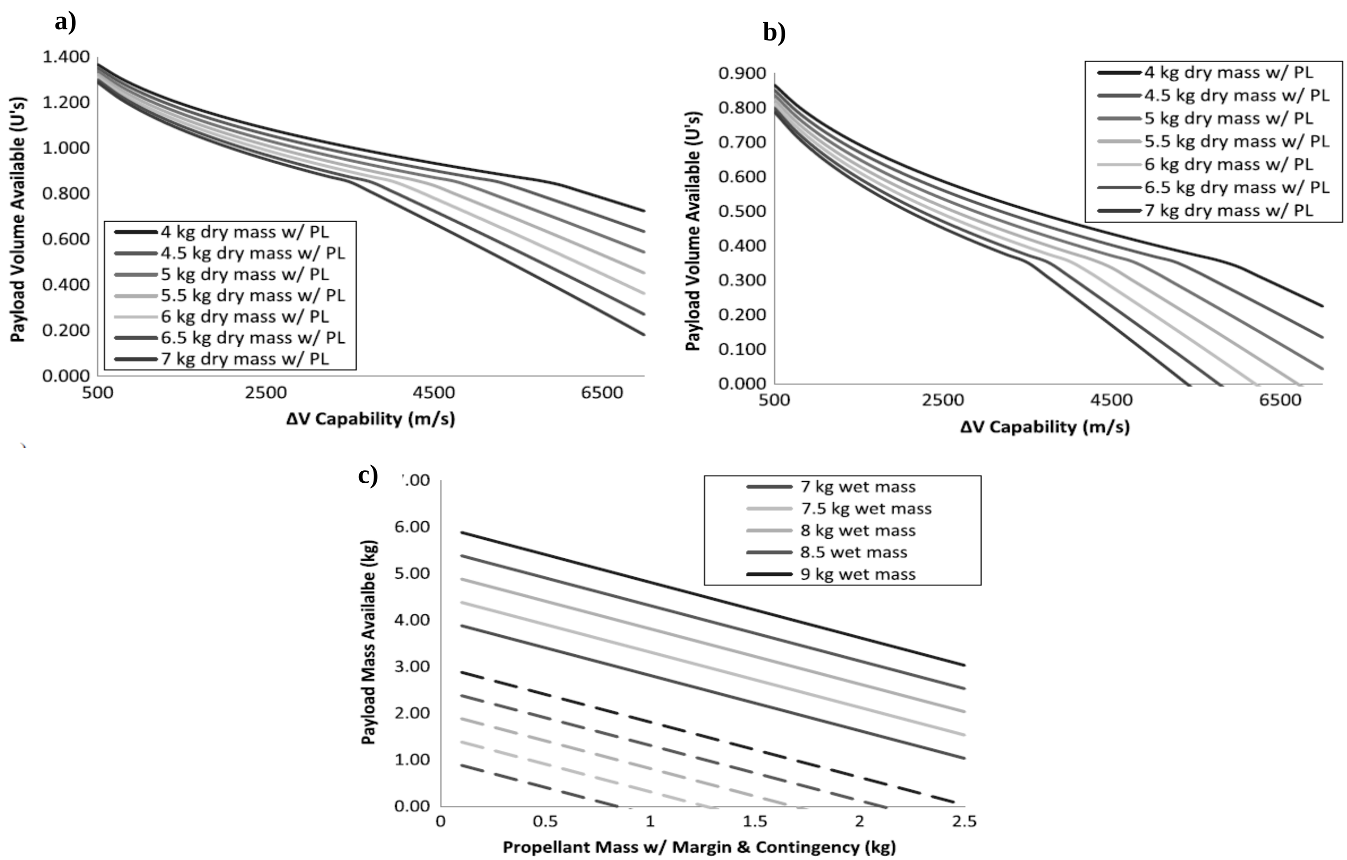

Fig. 7 a) Payload Volume vs. ΔV Capability with MiXI thruster in the outboard configuration, b) Payload Volume vs. ΔV Capability with MiXI thruster in the inboard configuration, c) Payload Mass Available vs. Propellant Mass[16]

As far as the system architecture of the 3U CubeSat capable of supporting the MiXI thruster is concerned, specific design tradeoffs must be deliberated with the mission requirements in mind. First, as the ΔV requirement increases for a given mission, the interior volume available for the useful payload decreases because of the increased volume required for the propellant tank (**Fig. 7, a and b**). This suggests a negative relationship between mission-required ΔV and payload capacity. Second, for a given flight mass, a relation exists between the payload mass available and the propellant mass required to generate a desired ΔV. To generate this relation, a spacecraft dry mass (including payload) must be assumed. Third, a positive relationship exists between the spacecraft's propellant mass and the ΔV or inclination change Δi capabilities.[17]

Fortunately, the MiXI thruster can be configured in two ways: the inboard and outboard configurations (**Fig. 8**). The outboard configuration creates more open volume within the CubeSat thus allowing more space for the payload as seen in the plot a in **Fig. 7**.

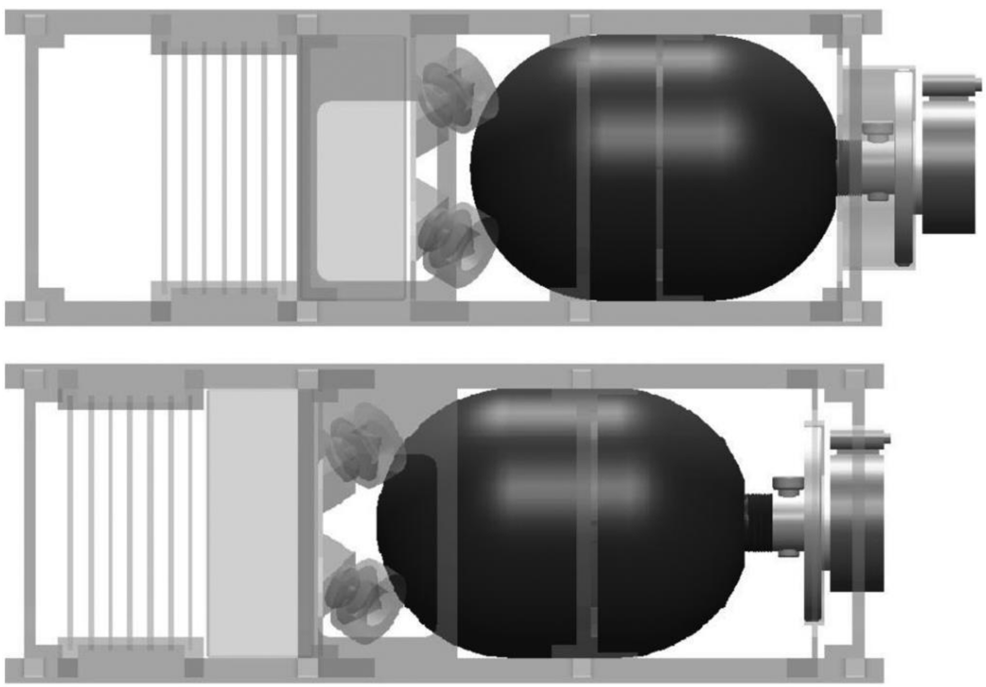

Fig. 8 High ΔV 3U CubeSat bus (ΔV of 6000 m⁄s) employing the MiXI thruster in the outboard (top) and inboard configurations.[18]

The outboard configuration also is the best design for integration of the thruster because it still fits within the dimensional limitations dictated for 3U CubeSats in the CubeSat Design Specification. The thruster would fit in what is called the, "soda can" section of the spacecraft. Because of this, a CubeSat employed with an outboard MiXI thruster can still fit within the standard, commercially available Poly-Picosatellite Orbital Deployer (P-POD) dimensions. The P-POD ensures the CubeSat conforms to all prescribed physical requirements and is the interface between the launch

---

[16] 17

[17] Conversano, Ryan W., and Richard E. Wirz. "Mission capability assessment of cubesats using a miniature ion thruster." *Journal of Spacecraft and Rockets* (2013).

[18] 17

vehicle and CubeSats. The standard P-POD holds up to 3U CubeSats which make this option still very available on market.

Other thruster options are compared in **Fig. 9** and the mini ion thruster proves to be the most desirable.

Thruster Technology	Thrust Range (mN)	Primary Thrust Control	Isp (sec)	Plume Divergence Half-Angle (°)	Propellant	Contamination Potential
Formation Flying Mission Targets	*0.01 - 1.1*	*Amplitude Modulated (AM)*	*> 1,000*	*< 20*	-	*Low*
Mini Ion	0.02 - 1.5 (0.001 – 0.1)	AM (also PWM)	2,500 - 3,500	5-15	Xenon	Low
Hall	4-17 (0.05 – 4)	AM (also PWM)	1,200 - 1,600	60-75	Xenon	Low (except for beam divergence)
Teflon PPT	~ 1 @ 1 Hz	Pulse Width Modulated (PWM)	650-1400	30-45	Teflon	High
Cold Gas	4.5 - 1000	PWM	65	45	Nitrogen	Low
Colloid	0.001-0.1	AM	100 - 500	18	Ionic Liquids	High
Cs- FEEP	0.1 – 1.4	AM	6,000 - 12,000	30-45	Cesium	Very High
In-FEEP	0.001 - 0.1	AM	4,000 - 12,000	30-45	Indium	High

Fig. 9 Other propulsion options that can be applied to CubeSats.[19]

VIII. Conclusion

The ALBus CubeSat is evidence that 100-Watt power management and distribution in the constricted volume of a 3U CubeSat is possible with an adequate thermal control system and system architecture and design. The ALBus CubeSat gives insight into what design considerations need to be taken in order to supply power to a high-power payload within a CubeSat. The MiXI thruster is not necessarily a 100-Watt power demanding, high-power payload, however, when coupled with other subsystems necessary for high impulse missions, the total power requirements can equal or transcend 100 W. Knowing that a 3U CubeSat can sustain the necessary subsystems as far as power goes, strengthens the case for using 3U CubeSats for various missions.

One shortcoming of this study is the lack of extensive exploration of the volume constraints associated with the utilization of 3U CubeSats. The reason for this is payload, propellant, and subsystem volume decisions rely heavily on the mission's requirements, needs and resources. The purpose of this study was to assess if using 3U CubeSats for various missions (geocentric transfer orbits, geosynchronous orbits, lunar transfers etc.) was feasible by analyzing whether a CubeSat could provide the basic necessities, like power and thermal control, for such missions. This was achieved through the analysis of the ALBus CubeSat and examination of options for the CubeSats propulsion system, a vital constituent for high impulse missions.

While in its current configuration, the ALBus CubeSat could not provide the volume needed for a MiXI thruster thus its system architecture cannot be duplicated for a high impulse mission. As said before, the ALBus CubeSat

[19] 92

circuit boards are strategically spaced apart since 100 Watts of waste heat is being dumped into a closed system and can result in severe overheating if the boards are too close together. This is not going to be true for all CubeSats since 100 Watts of waste heat is not always expected. It is also not mandatory that CubeSats are heavily populated with body mounted solar arrays which result in a closed volume. The reason for that design choice on behalf of the ALBus CubeSat team is the lack of a 3-axis attitude control system. Meaning, the satellite is always spinning so to ensure the arrays are exposed to sunlight as the solar arrays are on every external face of the chassis. This will not be necessary for any CubeSat containing a 3-axis attitude determination and control system.

What this study also fails to explore is different orbital environments. Considering a limited test time, only one orbit trajectory was modeled and explored. It would strengthen the credibility of the conclusions made if other temperature test limits were investigated and tested to prove that the electrical components could survive more severe orbital environments.

Appendix

Hot Dwell MATLAB Code

```
close all

DataYes1 = xlsread('DataYes1.csv');

HeatSinkL = DataYes1(:,2);
HeatSinkR = DataYes1(:,24);
Time = DataYes1(:,1);
ps1powerWAT = DataYes1(:,38);
maxpower = max(ps1powerWAT);

plot(Time,HeatSinkL)
hold on
plot(Time,HeatSinkR)
hold on

I_on=find(ps1powerWAT>5);
time_on=min(I_on);

I_off=find(HeatSinkL>=68);
time_off=min(I_off);

run_time_sec=time_off-time_on;
run_time_min = run_time_sec/60;

Cp=0.90;
mass_given=350;

MaxHeat = max(HeatSinkL);
MinHeat = min(HeatSinkL);

mass_calc=(max(ps1powerWAT)*run_time_sec)/(Cp*(max(HeatSinkL)-
min(HeatSinkL)));
Qa = (mass_calc*Cp*(max(HeatSinkL)-min(HeatSinkL)))/run_time_sec;
Qt =(mass_given*Cp*(max(HeatSinkL)-min(HeatSinkL)))/run_time_sec;

An = {'Max Heat (C)', 'Max Power (C)', 'Run Time (s)', 'Run Time (min)';...
    MaxHeat, maxpower, run_time_sec, run_time_min};
A = An';
xlswrite('Hot_Start_Run_Time', A)
```

Cold Dwell MATLAB Code

```
close all
clear
clc

Data = xlsread('ColdSet_to_SteadyState1.csv');
Time = Data(:,1);
Battery = Data(:,16);
Battery_Redundancy = Data(:,17);
Processor = Data(:,18);
Aux = Data(:,19);
RnR = Data(:,20);
Charging = Data(:,21);
HeatSink = Data(:,22);
HeatSink_Redundancy = Data(:,23);
Mid_Int_Chassis_R = Data(:,24);
Body_Solar_R = Data(:,25);
Depl_Solar = Data(:,26);
Chassis_RadioEnd = Data(:,27);
Depl_Solar_End = Data(:,29);

plot(Time, HeatSink, 'w')
hold on
plot(Time, HeatSink_Redundancy, 'w')
hold on
plot(Time, Battery, 'b')
hold on
plot(Time, Battery_Redundancy, 'b')
hold on
plot(Time, Processor, 'c')
hold on
plot(Time, Aux, 'm')
hold on
plot(Time, RnR, 'g')
hold on
plot(Time, Charging)
hold on
plot(Time, Mid_Int_Chassis_R, 'y')
hold on
plot(Time, Body_Solar_R, 'y')
hold on
plot(Time, Depl_Solar)
hold on
plot(Time, Chassis_RadioEnd)
hold on
plot(Time, Depl_Solar_End, 'r')
hold on
legend('HeatSink', 'HeatSink2', 'Battery', 'Battery2', 'Processor', 'Aux',
'Rnr', 'Charging', 'Int. Chassis', 'Body Solar', 'Depl Solar', 'Chassis Radio
End', 'Depl SolarEnd');

whitebg('k')

HSi = find(((HeatSink + 11) < -0.009),1);
HeatSinkColdest = HeatSink(HSi);

HSTimeReached_s = Time(HSi);
```

```
HSTimeReached_hr = HSTimeReached_s/3600;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% BMi = find(((Battery + 11) < -0.009),1);
% BMColdest = Battery(BMi);
%
% BMTimeReached_s = Time(BMi);
% BBTimeReached_hr = BMTimeReached_s/3600;
```

Acknowledgments

N.B.C. Author thanks the Embry-Riddle Aeronautical University (ERAU) McNair Program for sponsorship and financial support to perform this research project. Author also thanks entire NASA ALBus CubeSat team and Center for permitting the project to be conducted using NASA's state of the art facilities.

References

"ALBus CubeSat Thermal Analysis Document." *(unpublished)*. Cleveland: NASA Glenn, n.d.

Butler-Craig, Naia I. "ALBus CubeSat Thermal Vacuum Test Plan." *(unpublished)*. Cleveland: NASA Glenn, n.d. Document.

"CAD Model of ALBus CubeSat." *(unpublished)*. Cleveland: NASA Glenn, n.d.

Caron, R. "ELFIN Engineering Overview." *(unpublished)*. Institute for Geophysics and Planetary Physics, University of California, Los Angeles, 2010.

Conversano, Ryan W. and Richard E. Wirz. "Mission Capability Assessment of CubeSats Using a Miniature Ion Thruster." *Journal of Spacecraft and Rockets* 50.5 (2013): 1035-1046. 24 8 2017. <http://arc.aiaa.org/doi/abs/10.2514/1.a32435>.

Crowley, Geoff et al. "Dynamic Ionosphere CubeSat Experiment (DICE)." *25th Annual AIAA/USU Conference on Small Satellites*. Logan: AIAA, 2011. Document.

Heidman, Kelly. "ALBus CubeSat Will Demonstrate Power Technology." 17 July 2017. *nasa.gov*. Document. 25 July 2017. <https://www.nasa.gov/image-feature/albus-cubesat-will-demonstrate-power-technology>.

Lin, R. P. "CINEMA (CubeSat for Ion, Neutral, Electron, MAgnetic Fields)." *American Geophysical Union, Fall Meeting 2009*. San Francisco: American Geophysical Union, 2009. Document.

Mehrparvar, Arash. *CubeSat Design Specification Rev. 13*. Cal Poly San Louis Obispo, 2014. Document.

Swartwout, Michael. "The First One Hundred CubeSats: A Statistical Look." *Journal of Small Satellites* (2013): 213-233. Document.

Wirz, Richard E. "Miniature Ion Thrusters: A Review of Modern Technologies and Mission Capabilities." *Joint Conference of 30th International Symposium on Space Technology and Science*. Hyogo-Kobe: International Symposium on Space Technology and Science, 2015. Document.