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Thermal Modeling and Analysis of a Cube Satellite: Passive Thermal Coating Observatory Operating in Low Earth Orbit (PATCOOL)

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Abstract

The Passive Thermal Coating Observatory Operating in Low Earth Orbit (PATCOOL) CubeSat is a NASA-sponsored on-orbit experiment developed and led by the Advanced Autonomous Multiple Spacecraft Laboratory at the University of Florida. The CubeSat mission is intended to research the feasibility of using a cryogenic selective surface coating called Solar White as a way of enabling more efficient passive cooling of components in deep space. During ground experiments, this novel technology has demonstrated that it can provide a much higher reflectance of the Sun's radiation than any existing thermal coating or paint, and the PATCOOL CubeSat will validate this technology. The thermal design of PATCOOL is the most important aspect for mission success. The PATCOOL payload contains a four-sample housing with two samples coated in Solar White and the other two coated in state-of-the-art white thermal control coating: AZ-93. This paper discusses the process of building the thermal model, as well as the thermal analysis results of the PATCOOL CubeSat with industry standard thermal modeling software: Thermal Desktop®. The thermal analysis aims to investigate the steady state temperature response of the PATCOOL payload and to determine the sources of heat flux sources. The PATCOOL thermal analysis results for both the internal and external thermal models demonstrated that the cryogenic selective surface coating performed much more effectively compared to the current state-of-the-art in thermal paint, thus verifying the effectiveness of the PATCOOL thermal control design.

1. Introduction

In their study, Liebert and Hibbard (1962) suggested that a wavelength-dependent property of a specific selective surface could theoretically achieve and maintain a steady state temperature as low as 40K in deep space at 1 AU from the Sun. If demonstrated functionally on-orbit, selective surfaces can enable unprecedented capabilities, such as cryogenic propellant storage and superconductor operation without refrigeration in deep space. The Advanced

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Autonomous Multiple Spacecraft (ADAMUS) Laboratory at the University of Florida was funded by NASA Launch Service Program (LSP) to build and fly the PATCOOL CubeSat to test the performance of a NASA-developed experimental selective surface coating, from now on referred to as “Solar White.”

In 2015, Kennedy Space Center’s Dr. Robert Youngquist developed Solar White, which can theoretically reject more of the Sun’s irradiant power than any commercially available thermal coating or paint (Youngquist and Nurge, 2016). In 2016, NASA LSP funded the testing that would develop and quantify the performance of Solar White, which absorbs approximately 0.1% of solar energy in space (Youngquist and Nurge, 2016) compared to the best selective surfaces available which absorbs 7% of the Sun’s energy (AZ Technology). While Solar White has been proven in laboratory testing, a successful PATCOOL mission would raise the Technology Readiness Level (TRL) of Solar White from a 3-4 to a 5-6. NASA LSP approved the statement of work set forth by the University of Florida in 2018 to allow a team of undergraduate, graduate, and post-doctoral students to work on the PATCOOL CubeSat. Currently, the CubeSat has a launch date set for quarter three of 2021 as part of the Educational Launch of Nanosatellites (ELaNa) 37 mission to the International Space Station (ISS).

The payload of PATCOOL consists of a housing containing four thin cylindrical (coin-shaped) samples. Two of the small metallic samples are coated Solar White and the other two samples are coated with the current state-of-the-art in thermal coatings, AZ-93, as shown in Figure 1.

Thermal data for the samples will be collected and compared, with PATCOOL flying an orbit close to the ISS’s and the samples zenith pointing (i.e., radially away from Earth). The computer-based, high-fidelity thermal analysis for PATCOOL was performed using the industry standard thermal modeling software Thermal Desktop®, which uses AutoCAD and contains a thermal solver called SINDA/FLUINT.

This paper is intended to provide a resource to the thermal modeling procedures and analysis methods for a primarily thermal, or thermal coating-type

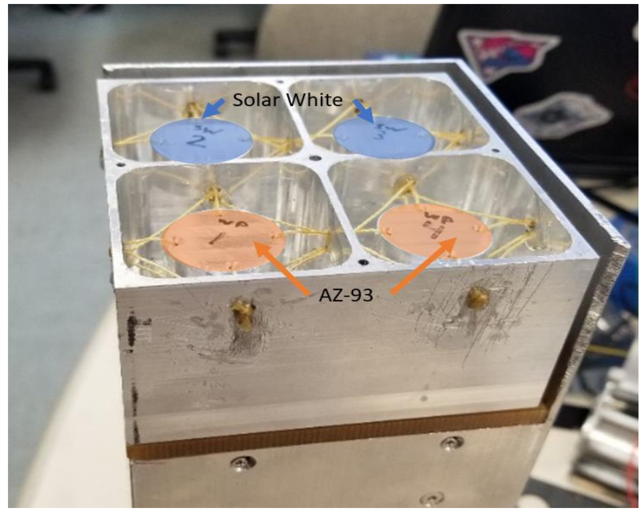

Figure 1. PATCOOL payload prototype with Kevlar strings tying the samples to the payload housing.

experiment. To fulfill mission requirements, the steady state temperature of the PATCOOL payload will be investigated, as well as the heat rate sources of the thermal samples and the tem-perature response of the internal electronics. The goal of this study is to assess the effectiveness of the PATCOOL thermal design in thermally isolating the experimental samples from the rest of the CubeSat and to demonstrate the use of Thermal Desktop® for the thermal analysis of a CubeSat. This paper serves a resource to students and academic teams working on CubeSat experiments to help guide the procedures for building and analyzing a thermal model that includes avionics and thermal coatings.

2. Background on PATCOOL’s Thermal Loads and Management

2.1. Thermal Environment in Space

The most important heat transfer dynamics in the space environment include radiation and conduction. Radiative heat transfer primarily drives the exterior of a fully enclosed CubeSat while conductive heat transfer dominates the internal environment (Weston et al., 2018). An energy balance approach is used in the thermal analysis to de-scribe the flow of heat entering and exiting all satellite interfaces, since they experience different heat transfer modes throughout the CubeSat mission lifetime.

The primary forms of external heating of a satellite in low Earth orbit (LEO) are related to sunlight: direct solar, the sunlight reflected off Earth (albedo), and the Earth infrared (IR) radiation (Gilmore and Donabedian, 2002). These three forms of heating are always balanced by the satellite's own infrared radiation back to space. Having effective thermal control on a satellite is a matter of whether the satellite's components are within their allowable temperature ranges when this balance is achieved. Variations in the Earth impact the albedo and IR emission, but typically average values are used. For well insulated components, these factors are not a large concern, but they may be for exposed components such as solar panels, so they must be considered in the thermal model.

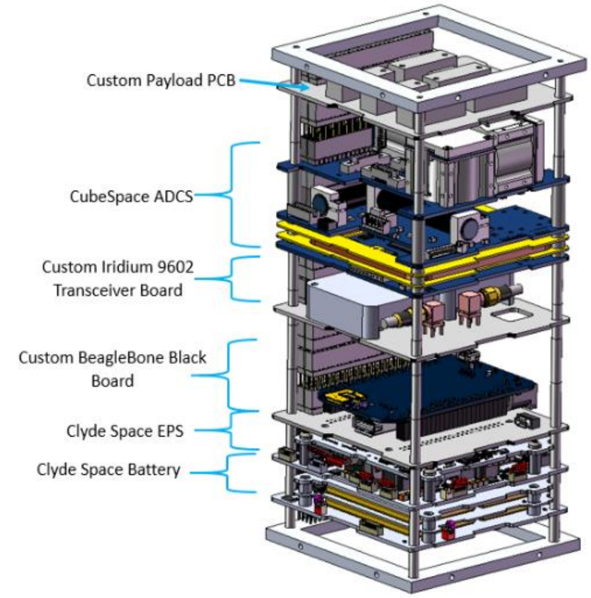

Figure 2. Avionics system of PATCOOL.

2.2. Thermal Management of Printed Circuit Boards (PCB)

A large subsystem of PATCOOL is the avionics package, which consists of a stack of printed circuit boards (PCBs) connected using standoffs and traditional PC/104 headers, as shown in Figure 2. There are four threaded rods in each corner of the PATCOOL avionics stack-up, which are fastened by M3 aluminum standoffs in between each PCB. The rods are then fastened into an avionics frame, which is then fastened to the CubeSat structure. This stack configuration means that all circuit cards are thermally connected in series and are interdependent (Weston et al., 2018). Each PCB acts as both a heat source, reflecting and emitting heat to neighboring satellite components, and heat sink, receiving heat from external sources such as the battery and indirect solar radiation. All components are designed to operate within a provided temperature range, so it is imperative to verify that the thermal requirements of the manufacturer are adhered to.

Thermal contact conductance between two different solid materials, rather than conductance within a solid material, drives the thermal conduction between PCBs in avionics stacks. Avionics stacks have small surface areas and high contact pressures, although there are many other factors that affect thermal contact conductance (such as surface cleanliness, surface deformation, and surface roughness). These intricacies make measuring the contact area difficult and as a result, conduct conductance values are usually found experimentally using different models/approaches. In this case, card-to-rod conduction values obtained experimentally by the European Space Agency were inputted into Thermal Desktop® for the PATCOOL thermal analysis (Hager, Flecht, and Janzer, 2019). The solid conductance of the aluminum standoffs is small in comparison, but still inputted as a nodal connection property in Thermal Desktop®.

2.3. Satellite Thermal Control

2.3.1. Thermal Insulation and Coatings

The thermal insulation and coatings used on PATCOOL consist of the two thermal coatings on the four payload samples as well as multi-layer insulation (MLI) manufactured by RUAG. Since the main external heat input for a satellite is absorbed solar radiation, it is important to quantify the solar absorptance and thermal emittance for any thermal control coatings or paints used on-board. The coatings must be laboratory tested to certify their use in space since most materials have a non-negligible amount of degradiation due to particle damage, outgassing, or ultraviolet radiation. They also must be tested in space to verify the space environmental impacts that affect them.

A few companies that specialize in manufacturing state-of-the-art thermal paints include Astral Technology Unlimited, MAP Space Coatings, and AZ Technology, though this list is not exhaustive. These companies have successfully flown their products in space, which gives them a TRL of 9. The current state-of-the-art thermal paint that PATCOOL will be using is called AZ-93 by AZ Technology, which will be directly compared to Solar White. Both coatings reflect radiant heat from the Sun while allowing some far-infrared heat emission to occur, but AZ-93 paint still has significant heat emission in non-visible radiation bands. Currently, the state-of-the-art in thermal paints has not been able to allow spacecraft to maintain cryogenic temperatures in space (Youngquist and Nurge, 2016). The optical properties of AZ-93 and Solar White are listed in Table 1.

Table 1. Optical properties of AZ-93 and Solar White

Material	**Solar Absorptivity α**	**IR Emissivity ε**
AZ-93	0.15	0.91
Solar White	0.01	0.6

2.3.2. Selective Surfaces

Selective surfaces have been developed for use on Earth to provide high emissivity in the nonvisible portion of the Sun's spectrum and low absorptivity in the visible spectrum. They absorb and emit low amounts of solar energy while reflecting most of the solar energy, and they also both absorb and emit well in the far infrared. Their absorbance, emittance, transmittance, and reflectance values are tailored to take advantage of different wavelength intervals to meet mission temperature demands, hence spectral selectivity (Granqvist, 1981). On Earth, selective surfaces do not work as theoretically intended, due to the effects of convection, condensation, and infrared emission. The vacuum-like conditions of space make selective surfaces ideal for testing and have already been flown onboard the Space Shuttle Orbiter and the Hubble telescope. For both of these examples, the selective surface was a transparent plastic with an aluminum or silver backing, but it did not reject enough solar energy to maintain cryogenic temperatures (Youngquist and Nurge, 2016).

On PATCOOL, Solar White is comprised of a transparent material that scatters most of the Sun's radiation and a metallic reflector underneath it to reflect longer wavelengths of solar radiation that are not as well scattered. Solar White is based on the concept of commonly used white paint, which offers low absorption in the visible radiation bands and high emission in the nonvisible radiation bands. Youngquist and Nurge (2016) studied how light scatters in an isotropic homogenous material and determined the optimal particle size for scattering most of the Sun's visible energy which would eventually be used in Solar White.

2.4. Mission Overview

The primary objective of the PATCOOL mission is to characterize and demonstrate the performance of Solar White and its potential for future space applications. Solar White will be applied to a set of samples that will serve as part of the payload and which have been designed to maximize thermal isolation from the rest of the CubeSat. The CubeSat must be designed to shield the samples from Earth's thermo-optical effects, minimize heat transfer from the CubeSat structure and electronics to the payload, and include sensors to record temperature readings from various areas of the payload. The mission concept of operations, or CONOPS, is illustrated in Figure 3. The CONOPS describes each phase of the mission and the requisites for each phase from launch to eventual satellite decay.

3. PATCOOL Design

3.1. Overview of Subsystems

The subsystems of PATCOOL support the primary mission objective while accounting for the limitations of size and weight of a CubeSat with a 3U form factor. They are comprised of: (1) the payload; (2) the CubeSat structure; (3) the solar panels; and

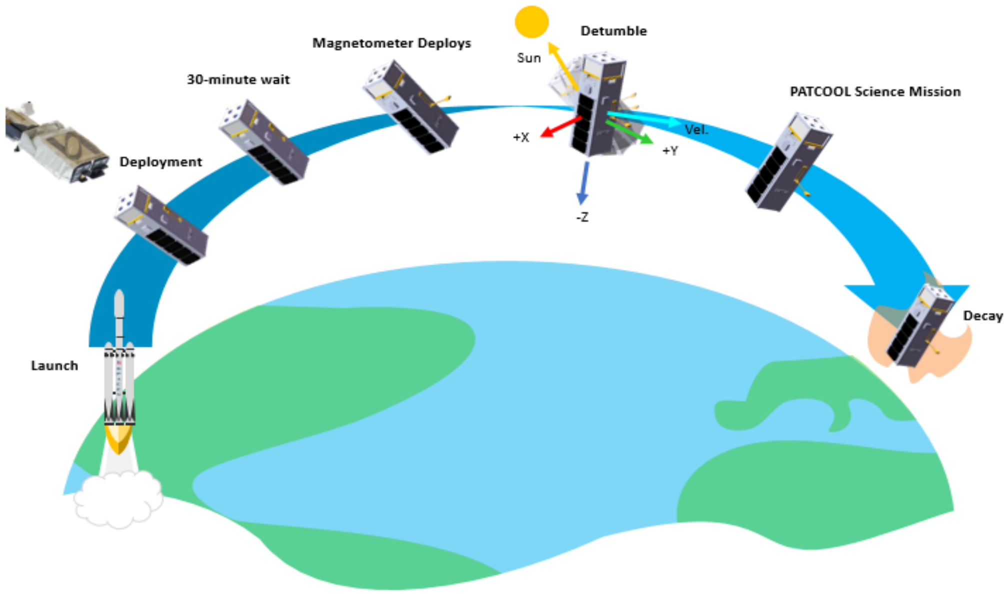

Figure 3. Visualization of PATCOOL mission CONOP

(4) the avionics, as shown in the CubeSat high-level component view in Figure 4. PATCOOL will be launched inside a NanoRacks deployer, so it must conform to NanoRacks requirements to ensure proper interfacing and ISS flight safety (NanoRacks).

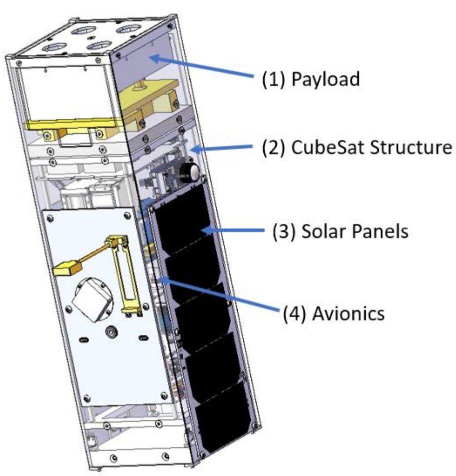

Figure 4. Top-level view of PATCOOL and subsystems.

3.2. Payload Summary

The PATCOOL payload consists of an aluminum housing structure that hosts four sample disks, two of which have outer surfaces completely coated in Solar White while the other two are completely coated in AZ-93 white thermal paint for comparison. Each sample is suspended within a quadrant of the housing with Kevlar strings (selected for its high tensile strength and low thermal conductivity) and measures 25 mm in diameter and 10 mm in thickness. Inside each sample is a temperature sensor which will be used to measure temperature response during the CubeSat's science mission.

The sample housing was designed so that all four samples experience identical or near-identical radiative heat from the Sun and conductive heat from the housing. There are two sides of the housing that will be exposed to the Sun and facing away from Earth while the CubeSat is in orbit. These sides are coated in AZ-93 paint to allow radiative heat to dissipate more effectively than bare aluminum. On top of the housing is an aluminum top cover, which is also coated in AZ-93 paint, that has four 20 mm diameter circular cutouts above each sample to expose the four samples to the Sun. The samples see more radiative heat with a top cover rather than without it due to the heat transfer from the top cover to the housing. An adapter made of Ultem is located directly below the housing to minimize conduction between the CubeSat structure and the housing and ensure there is no direct contact between the two interfaces. Ultem was chosen as the adapter material for its ability to withstand high heat and its low conductivity. The CAD model of the payload is shown in Figure 5.

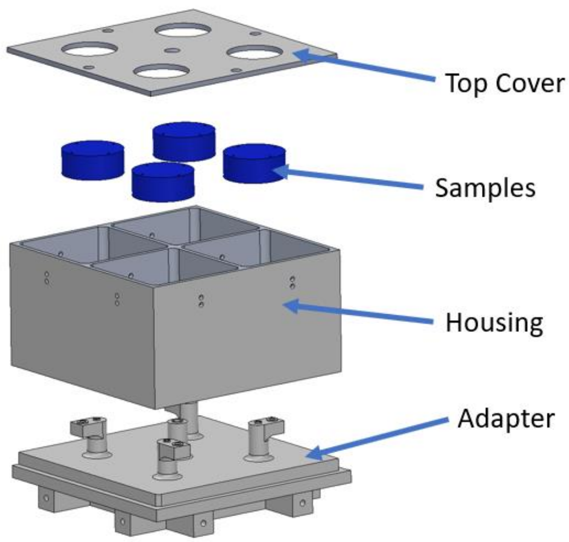

Figure 5. Expanded view of PATCOOL payload components.

The sample housing and the inside of the top cover will be electroplated with silver since it has the best reflecting properties of all solid metals and the lowest absorptivity and emissivity values when electroplated on a surface, which will allow the housing to radiate minimal heat to the samples (Zimmermann, 1955). For an extra measure of thermal isolation, a thin, plate-like aluminum heat shield will be placed below the Ultem adapter and above the top of the avionics frame. The heat shield is conductively coupled to the CubeSat structure so that internal heat generated by the electronics stack-up can escape into deep space instead of being radiated by the payload.

3.3. Structure and Solar Panels

The PATCOOL structure is made of an aluminum square tube that adheres to the 1x3x1U CubeSat form factor and houses the payload and avionics. Between the structure and the payload is a multi-layer sheet of MLI blanket folded in half, as shown in Figure 6, that further shields the payload housing from the structure on the Sun-facing sides of the CubeSat.

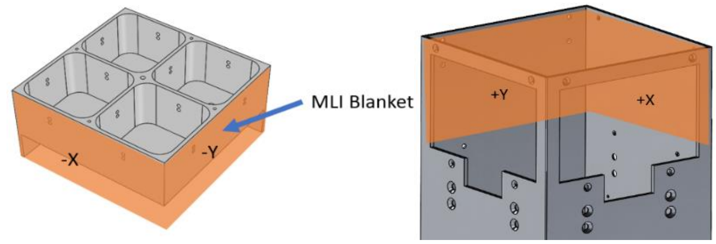

Figure 6. MLI blanket sheet shown on the housing (left) and CubeSat structure (right).

There are two 2U and one 3U solar panels fastened to the CubeSat structure, as shown in Figure 7. These solar panels are COTS components from AAC Clyde Space, and are configured so that power is generated on orbit while space is conserved for external components such as the antennas, Sun sensor, access ports, and deployable magnetometer.

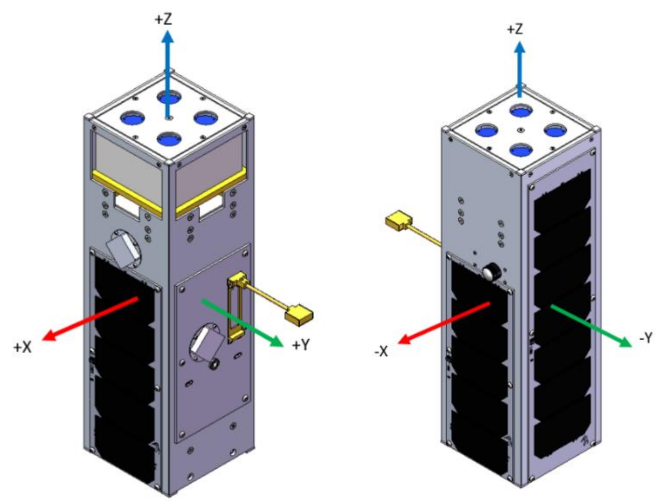

Figure 7. View of two 2U solar panels and one 3U solar panel (right) with corresponding body axes.

3.4. Thermal Requirements

A basic approach to CubeSat thermal control begins with identifying the thermal environment that the CubeSat experiences in orbit and establishing temperature requirements that the science mission must adhere to.

To fulfill the payload shielding requirement, the CubeSat hosts an attitude determination and control system (ADCS) from CubeSpace that integrates reaction wheels, magnetorquers, a Sun sensor, and a deployable magnetometer to point the CubeSat such that the samples are always facing away from the Earth (zenith pointing).

Another component to the CubeSat thermal analysis is determining whether the selected COTS avionics operate within the specified manufacturer temperature ranges, which are listed in Table 2. It is important to note that these temperature ranges have not been verified through testing, so they may not all accurately reflect the space thermal environment.

Table 2. Component-Level Operating Temperatures of COTS Avionics

Component	Minimum Operating Range (K)	Maximum Operating Range (K)
BeagleBone Black Industrial	233.15	358.15
Iridium 9602N Transceiver	233.15	358.15
TW1600 Ceramic Patch Antenna	233.15	358.15
CubeSpace CubeADCS 3-Axis	263.15	333.15
Clyde Space 3G EPS	263.15	323.15
Clyde Space 20Whr Battery	263.15	323.15
Clyde Space Solar Panels	233.15	353.15

4. Approach to Thermal Analysis

The workflow for a thermal model in Thermal Desktop® begins with constructing representative geometries (such as CubeSat walls and other structural components), assigning materials, and establishing nodes, conductors, and contactors. Then, the orbit properties are defined depending on the CubeSat attitude and the heating cases. The temperature plots and temperature distribution for the CubeSat can then be obtained, but to find the heat rate sources of the thermal samples, the Logic Manager in Thermal Desktop® must be used to output various heat fluxes.

4.1. Literature Review

A comparison of five thermal analysis studies from university CubeSat teams around the world is presented in Table 3 to show the thermal analysis software used, the number of nodes in the thermal model, if mentioned, and a summary of the approach to thermal analysis.

The thermal modeling approach used in this study combines several of the techniques used in the papers by Rogers et al., Chandrashekar, and Kang. The thermal analysis approach is most similar to that of Rogers et al., in that both CubeSats are modeled with simplified geometries, and the heat loads for each PCB is uniformly distributed across each board. In Chandrashekar's paper, the card-to-rod conductance values were obtained experimentally and then inputted into the thermal modeling software; however, these values could not be used for PATCOOL because the mounting configuration of the PCBs is different. In the paper by Kang, the contact conductance values were calculated for each fastener, but it is unclear how these values were calculated and they were very low compared to the values in Chandrashekar's paper.

4.2. Heating Cases

To determine the variation in temperature for different launch dates throughout the year, a hot case, a cold case, and a nominal case were established. The most realistic launch date of around August 1, 2021 was established, based on potential 2021 ISS missions proposed by NanoRacks, and represents the nominal case. The temperatures of the hot and cold cases give insight on whether the CubeSat temperatures are sensitive to variations in launch date or weather, since those are factors that are out of control of the UF PATCOOL team. The hot case represents the maximum power output for the CubeSat avionics and a launch date during the warmest time of the year (September 23), while the cold case represents the minimal power output of the CubeSat avionics and the coldest time of the year (December 22). The solar constant, Earth albedo, and IR planetshine values were obtained from literature and are based on historical data (Gilmore and Donabedian, 2002).

Table 3. Literature Review of various CubeSat Thermal Analysis Approaches

Paper	Software	Number of Nodes in Model	Approach
Dinh (Dinh, 2012)	Ansys Icepak, Thermal Desktop®	N/A	• Thermal analysis decoupled into two cases: (1) internal heat conduction and radiation of the electronics using Ansys Icepak and (2) external heat radiation using TD • Calculated the heat flux on each side individually and uniformly applied the average heat flux to all sides of the CubeSat
Boushon (Boushon, 2018)	Thermal Desktop®	2294	• Began with analyzing single-node thermal model, followed by eight-node and multi-node analysis • No standoffs between avionics PCBs, only bolted-joint and adhesive contact
Rogers et al. (Rogers et al., 2020)	Thermal Desktop®	668	• Calculated in-plane conductivity values of each avionics PCB using known total thickness of copper and dielectric layers • Applied heat load locations across each entire board • Adjusted for thermal mass of PCBs
Chandrashekar (Chandrashekar, 2017)	Siemens NX	N/A	• Used a meshed computer aided design (CAD) model instead of building in thermal software • Conducted experiment to find contact conductance values that are inputted into thermal modeling software (e.g. between a PCB and its mounting screw)
Kang (Kang, 2016)	Thermal Desktop®	420	• Calculated contact conductance values for each fastener type (washers, standoffs, adhesive bonding) and inputted into TD as node-to-node conductor; unclear on how contact conductance values were calculated • Validated TD results with thermal vacuum test

4.3. Performing the Thermal Analysis

The thermal model used for this analysis simplifies the components of the CubeSat into multiple panels and cylinders connected by nodes. An alternative approach would be to apply meshes to represent CubeSat geometries at the cost of more computing time and power for similar results according to thermal simulations performed by LSP. The workflow for the PATCOOL thermal model began with constructing the model (consisting of CubeSat walls, avionics, payload geometry) and creating nodes, conductors, and contactors. The thermophysical properties in the thermal model include each material's density, conductivity, and specific heat capacity, while the optical properties include solar absorptivity and IR emissivity. Conductors and contactors are used in the thermal analysis to represent fasteners, with conductance values obtained from literature (Gilmore and Donabedian, 2002). Then the orbit properties are defined in Thermal Desktop® based on a Keplerian ISS orbit. The Logic Manager in Thermal Desktop® allows one to define the nodes for calculation of heat fluxes throughout the payload. The start interval for each hot, cold, and nominal case was set from 0 to 259,200 seconds for the PATCOOL 72-hour science mission duration when thermal data will be collected.

To model the avionics stack inside the CubeSat, thin shell rectangles represent each PCB. The material for each board was set to FR-4 (PCB material), although including this property is negligible from a temperature output perspective. Since the mass of FR-4 does not represent the total mass of each board plus the components mounted on them, such as reaction wheels, battery cell packs, etc., a density multiplier was added to correct the thermal mass and match the actual masses listed on supplier datasheets.

The power dissipation of the avionics stack is represented by a heat load distributed across the

PCBs according to the average and maximum power consumption based on component datasheets. An aluminum avionics frame encases the set of boards and is thermally connected to the square tube structure of the CubeSat with node-to-node contactors. The PCBs are connected to each other via node-to-surface conductors from which the card-to-rod contact conductance values were inputted for aluminum spacers of similar height. The spacer conductance values were inputted for the sake of comprehensiveness but may also be omitted from the thermal model. Finally, a battery heater was applied to the battery boards since there is a built-in heater on the Clyde Space 20 Whr battery.

5. Thermal Analysis Results

Recalling the criteria for mission success, PATCOOL must minimize heat transfer between the payload samples and the rest of the CubeSat. The results from the thermal analysis will verify where and how heat is being transferred to the payload samples and will also ensure that the CubeSat avionics are within their manufacturer operating temperature ranges. Another important question that the thermal analysis will answer is how the Solar White coated samples perform versus the AZ-93 coated samples for different launch date and conditions. The results of the thermal model were compared to those of Kevin Bauer of NASA LSP, who used a node-meshing approach to the .STEP file of the CubeSat rather than the "ground-up" approach used in this study.

Beta angles of 0.095°, -21.9°, and 28.2° were used for the hot case, nominal case, and cold case, respectively shown below in Figure 8. These beta angles were chosen based on potential launch dates for 2021. The thermal model as shown in Figure 9 represents the CubeSat design configuration which features three total solar panels (two 2U panels and one 3U panel) and a tip mass at the bottom of the Cu-

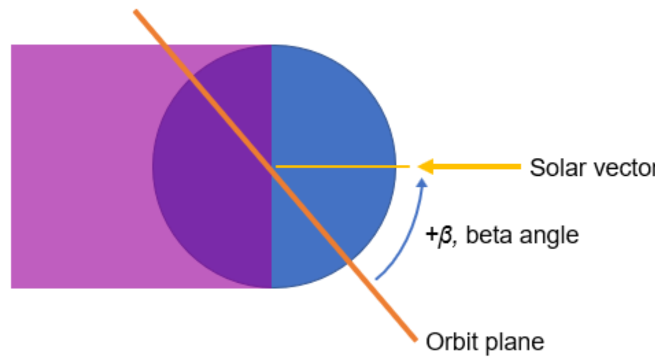

Figure 8. Orbit beta angle β with respect to the satellite orbit plane and solar vector.

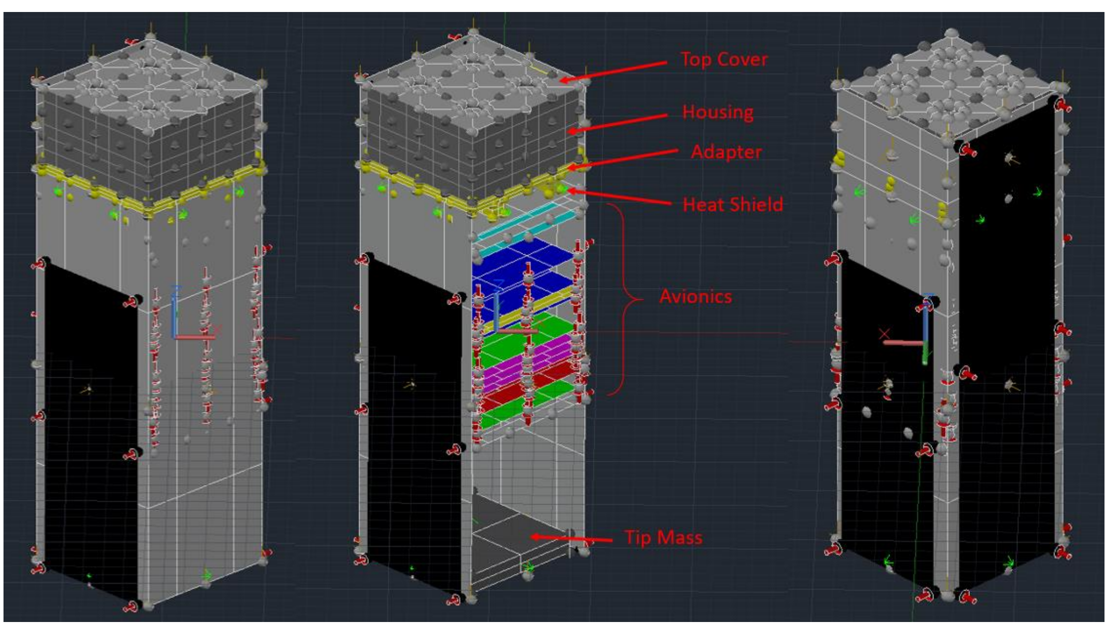

Figure 9. Thermal model of PATCOOL showing conductors, contactors, and heat loads.

beSat to keep the center of gravity within NanoRacks requirements. The PATCOOL thermal model contains 668 total nodes which created results to maximize processing power and ease of use.

5.1. Temperatures of PATCOOL

The temperature plot for PATCOOL was generated for the 72-hour mission duration as seen in Figure 9 for the nominal case. The most variation in temperature is seen in the adapter-housing interface, where the temperature gradient is shown in Figure 10. The payload adapter provides the most temperature difference out of all of the single components of the CubeSat due to its unique physical geometry and the low conductivity of Ultem.

5.2. Temperatures of the Payload

The payload housing, top cover, and four samples are the primary areas of interest for the PATCOOL thermal analysis. The temperature plot for each of these areas is shown in Figure 11 as the average of the nodal temperatures for each single component. This assumption is valid since all of the payload components are made of high-conductivity aluminum, so the temperature distribution within each component is mostly uniform. The nominal, hot, and cold cases of the payload over the 72-hour science mission is shown in Table 4.

Looking at Figure 11, the components of the payload begins to truly level off in temperature (quasi-steady state) at around 200,000 seconds. Table 4 shows that the temperature difference is minimal between the housing, top cover, and AZ-93 sample, especially when comparing to the entire range of temperatures that the solar panels experience. Between samples of the same type of coating (two of each type), the temperature variation is minimal, with a temperature difference of 0.68 K for the Solar White samples and 1.3 K for the AZ-93 samples. The temperature difference between Solar White and AZ-93 is 32.6 K for the nominal case, a considerably large gap for an area of the CubeSat that is directly exposed to the Sun.

The optical properties of the coatings themselves have a greater effect on temperature than the placement of the samples or the suspension of the samples with low-conductivity Kevlar strings. The top cover, the housing, and the AZ-93 samples are very similar in temperature (less than 2 K difference) because they are each coated with AZ-93 paint and are dominated by its optical properties. The temperatures of the AZ-93 samples are only slightly higher than those of the housing and top cover because they receive more radiative heat from the Sun over a smaller surface area.

As a confidence check, consider the temperatures of a Solar White sample and an AZ-93 sample in

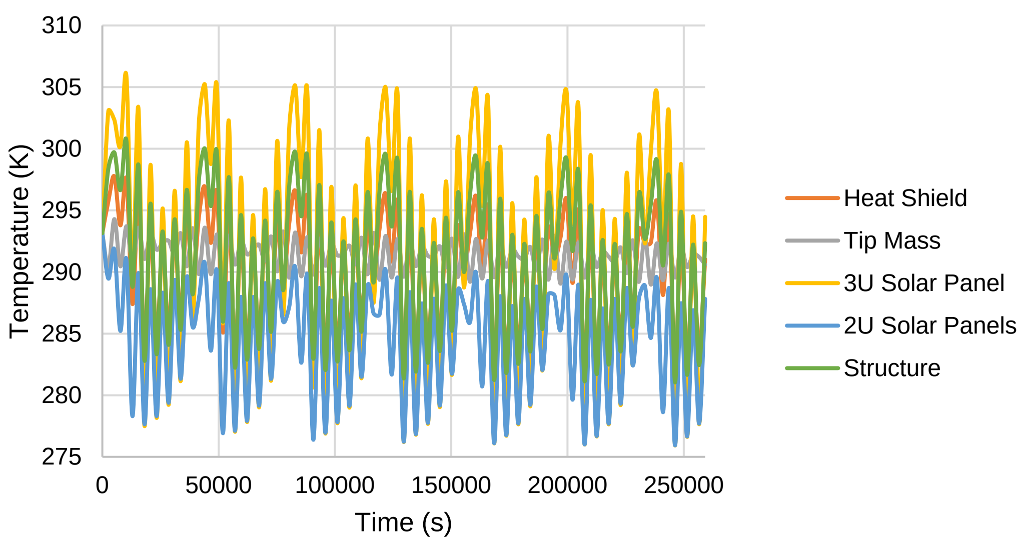

Figure 10. Temperature versus time for various CubeSat components under the nominal heating case.

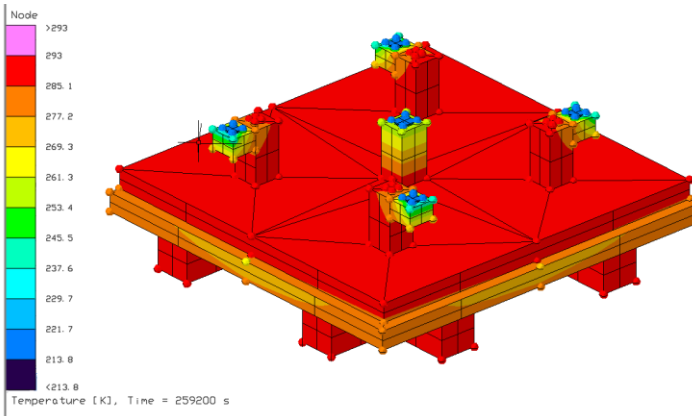

Figure 11. Temperature distribution for the housing adapter at the end of the CubeSat mission; nominal heating case.

deep space looking directly at the Sun (no CubeSat). B y using the following equations to solve for T_{sample}, the steady state temperature of the Solar White sample is 141.6 K and the temperature of the AZ-93 sample is 251.1 K.

$$Q_{in} = \alpha K_{Solar} A$$

$$Q_{out} = \varepsilon A \sigma \left(T_{sample}{}^{4} - T_{deep\ space}{}^{4} \right) = Q_{in}$$

When completely isolated and unobstructed by a CubeSat, two thermal samples have a larger temperature gap of 109.5 K under nominal conditions compared to the simulated 32.6 K temperature difference. Considering all the factors that affect spacecraft temperatures at low Earth orbit, it is difficult to assess whether the CubeSat design isolates the samples as best as it possibly can when compared to a hand calculation, but the temperature ranges obtained through this analysis fall within a reasonable ballpark.

5.3. Temperatures of Avionics

The temperature range of each component throughout the CubeSat mission duration is shown in Table 5. These temperatures were derived from the minimum and maximum temperatures values for each avionics component. The internal thermal analysis of the CubeSat proves that even if an uncertainty margin of 10 K was applied, the PATCOOL avionics would still be within the manufacturer specified temperature ranges for the hot, cold, and nominal cases.

Table 4. Quasi-steady State Temperatures of the Payload

Case	Housing Temp. (K)	Top Cover Temp. (K)	AZ-93 Sample 1 Temp. (K)	Solar White Sample 1 Temp (K)
Nominal	215.0	214.7	215.9	183.3
Hot delta Temp. from Nominal	3.15	3.14	3.78	2.51
Cold delta Temp. from Nominal	-3.30	-3.43	-4.34	-2.86

Table 5. Resulting Temperature Ranges of COTS Avionics

Component	Manufacturer Operating Range (K)	Nominal Case Temperature Range (K)	Hot Case Temperature Range (K)	Cold Case Temperature Range (K)
BeagleBone Black Industrial	233.15→358.15	290→302.5	293.1→317.1	287.5→301
Iridium 9602N Transceiver (2)	233.15→358.15	290→296.4	292.9→310	287.5→296
CubeSpace CubeADCS 3-Axis	263.15→333.15	290→294	292.8→294.8	287.6→293.8
Clyde Space 3G EPS	263.15→323.15	290→294.4	292.8→295.9	287.6→294.2
Clyde Space 20Whr Battery	263.15→333.15	290→293.4	292.9→294.8	287.6→293.4
Clyde Space Solar Panel	233.15→353.15	276.2→305.9	276.4→313.5	271.1→304.8

5.4. Heat Fluxes of Payload

As mentioned previously, the heat fluxes of the payload samples were obtained to find out which modes of heat transfer and where dominate the temperature results shown above. A MATLAB script was provided by NASA LSP to calculate the net heat value outputs from Thermal Desktop®. A subroutine within the Thermal Desktop® Logic Manager was run from 259,200 to 309,200 seconds (50,000 seconds past the mission duration) so that the temperatures could reach a quasi-steady state when plotted with MATLAB. The MATLAB code utilizes the following equation to find the net heat outputted by Thermal Desktop®:

$$Q_{net} = q_{housing} + q_{cover} + q_{string} - q_{space}$$

The net heat flux, Q_{net}, theoretically should be as close to zero as possible to ensure that the net heat summation is accurate to the net heat produced by Thermal Desktop®.

Tables 6 and 7 show the heat flux results for the hot, cold, and nominal cases for the Solar White and AZ-93 samples, respectively. Looking at the heat flux results from the tables, the radiation from the housing to the samples is the dominant mode of heat transfer to the samples for all heating cases and for both types of thermal coating. The second largest source of heat to the samples is the conduction from the Kevlar strings, followed by the radiative heat from the top cover.

The reason why the energy sources in these tables are not non-zero is because the net heat equation only accounts for the heat transfer of the housing, strings, and top cover to the samples. It does not account for the effects of Earth's albedo, internal radiation, or Earth's infrared energy, so there is a source of heat missing that is coming from these factors. Since Earth's albedo and infrared are tabulated as average values instead of being plotted over time, the thermal analysis does not account for variations in cloud cover, ocean cover, and seasons that make accurately quantifying these values a difficult task.

5.5. Discussion

Performing the thermal analysis of PATCOOL yielded very similar results compared to LSP's thermal model. The temperature difference between the AZ-93 samples and the Solar White samples was about 35 K compared to this study's 32.6 K sample temperature difference, which is a close comparison for two thermal models using two different approaches. The only way to verify that both models are truly accurate to the physical CubeSat is through physical testing in a thermal vacuum chamber before the launch of PATCOOL. As for the quasi-steady state heat fluxes of the samples, the thermal analysis

Table 6. Quasi-steady State Heat Transfers of Solar White Samples

Case	Sun Energy to Sample (mW)	Radiation from Top Cover (mW)	Radiation from Housing (mW)	Conduction through Strings (mW)	Radiation to Space (mW)	Energy Sources (mW)
Nominal	6.927	0.089	0.511	0.243	2.945	4.824
Hot	7.190	0.097	0.551	0.250	3.147	4.943
Cold	6.673	0.083	0.469	0.236	2.748	4.711

Table 7. Quasi-steady State Heat Transfers of AZ-93 Samples

Case	Sun Energy to Sample (mW)	Radiation from Top Cover (mW)	Radiation from Housing (mW)	Conduction through Strings (mW)	Radiation to Space (mW)	Energy Sources (mW)
Nominal	117.8	-0.034	-0.270	-0.085	11.36	106.07
Hot	122.2	-0.031	-0.246	-0.074	11.86	110.01
Cold	113.4	-0.036	-0.285	-0.094	10.80	102.18

proved that the samples are mostly impacted by radiation from the housing. This means that changes to the physical design of the housing could greatly impact the temperatures that the samples experience in space. The internal CubeSat thermal analysis proved that the PATCOOL avionics did not overheat nor were they too cold in space, serving more of a sanity check to ensure that the samples are isolated from the heat of the avionics while powered on. Comparing the hot, cold, and nominal cases, the payload samples do not see a considerable difference in temperatures due to factors that are out of the control of the PATCOOL thermal control design.

It is worthwhile to note that the nodal resolution used in this study's thermal model was chosen based on processing power and ease of use. Boushon's paper (2018) from the literature review showed that increasing nodal resolution in Thermal Desktop® decreased overall temperatures, but increasing the number of nodes from 620 to 905 in this thermal model made a negligible effect (less than 0.5 K difference) to the payload sample temperatures. As a potential future work task, the nodal resolution of the thermal model can be increased until there are no noticeable differences in the temperature results.

6. Conclusion

This paper is intended to contribute to the state-of-the-art in CubeSat thermal control design by adding to the body of knowledge of CubeSat thermal modeling and analysis. By looking at PATCOOL, one can assess the effectiveness of thermal control design elements such as thermal coatings, material selection, and mechanical design. The purpose of the thermal analysis of PATCOOL is to predict the temperature variations of a vehicle in orbit and to determine the heat sources of four zenith-pointing samples inside the payload coated with two different thermal coatings. The results of the analysis demonstrate that that the experimental thermal coating (Solar White) samples perform 30.K more effectively than the samples coated with the current state-of-the-art in white thermal paint, AZ-93. The analysis also confirms that the internal electronics did not exceed their operational ranges during the science mission. The main takeaway for the quasi-steady state heat transfers for the samples is that there is more radiative heat from the sample housing than conductive heat from the strings, which means that the samples are effectively thermally isolated from the rest of the CubeSat.

To further refine the thermal model, additional model revisions can be made to more accurately model the CubeSat internal electronics, the number of nodes can be increased to give the model more of a temperature gradient across components, and the power dissipations can be applied to individual chips instead of across each PCB to add fidelity. Over the course of PATCOOL development, there have been many proposed updates to the mechanical design of the CubeSat, requiring an iterative process of designing, analyzing, and re-analyzing the thermal model to ensure that it correlates with the physical CubeSat. The thermal analysis can then be used to justify proposed design changes and make the most informed decisions for mission success.

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