Thermal Control for a Miniaturized Fabry-Perot Interferometer in a CubeSat

Callie Pilkington
Western Michigan University

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“Thermal Control for a Miniaturized Fabry-Perot Interferometer in a CubeSat”

Western Michigan University

College of Engineering and Applied Sciences

AE 4800 – Senior Design

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Industry Advisor: Dr. Wilbert Skinner, Michigan Aerospace
Disclaimer

This project report was written by students at Western Michigan University to fulfill an engineering curriculum requirement. Western Michigan University makes no representation that the material contained in this report is error-free or complete in all respects. Persons or organizations who choose to use this material do so at their own risk.
Acknowledgements

Our group would like to give a special thanks to our industry advisor Dr. Wilbert Skinner for the significant amount of assistance he has provided over the course of the project duration. Dr. Skinner was able to respond to all our many questions in a timely manner while also providing useful insight to how we should think about achieving our goal. Dr. Skinner was also able to provide our group with a limitless amount of information regarding small form factor satellites. Without the assistance of Dr. Skinner, our progress towards our goals would not have been as consistent as it was.

Our group would also like to thank Dr. Jane Pavlich and Dr. Will Johnson for their resourcefulness and challenging our group to think outside the box. Near the end of our project timeline, both people were able to provide our group with ideas to take steps to get even closer to our goal than what we thought was possible. Their encouragement also gave us the motivation to finish strong in the last weeks of our project timeline.

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Abstract

The evaluation of neutral winds is critical in understanding the ever-changing weather and climate of the thermosphere, which can develop into a hostile environment for satellites. To measure these neutral winds, Michigan Aerospace Corporation is developing a 6U CubeSat that utilizes a miniaturized Fabry-Perot interferometer. For ideal operation, the Fabry-Perot interferometer requires a closely maintained thermal environment. These requirements are crucial in obtaining accurate measurements and for sustaining instrument and mission life due to the vast temperature range experienced in the thermosphere.

With the solutions outlined in this proposal, the goal is to provide Michigan Aerospace with an optimized configuration of thermal control designs to conform to the strict temperature requirements proposed. Estimations of the temperature of the CubeSat through orbit will be simulated through SatTherm. Verification of the optimal configuration of passive and active designs will be done by extensive thermal modeling through the SOLIDWORKS Thermal Analysis package.
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1. Mission Overview

1.1. Background

The Thermosphere, a region of the Earth’s atmosphere located approximately at an altitude of 75 to 800 kilometers, is home to many low Earth orbiting (LEO) satellites. Satellites that reside in the Thermosphere are constantly at risk of being subjected to powerful winds and weather changes that may affect their orbital trajectories and ultimately shorten their mission lifespans. Much like weather phenomena in the lower atmosphere, the behavior of Thermospheric winds is unpredictable. Models developed to characterize the weather in the upper atmosphere can estimate factors over a large period such as decorrelation time (the time length of weather fluctuations) but struggle when tasked with determining the weather on a specific day. The desire to create a more accurate model for predicting Thermospheric weather creates a demand for greater observation capabilities of the upper atmosphere. The added benefit of an enhanced Thermosphere observation system is that a better correlation will be able to be drawn between the conditions in the upper atmosphere and the conditions in the lower atmosphere, leading to better prediction models for weather that is experienced on the ground.

To meet this demand Michigan Aerospace has developed a Fabry-Perot interferometer, or etalon, suitable for use on a 6 Unit (U) CubeSat that will be capable of measuring the wind that occurs in the Thermosphere. Although Thermospheric winds laboratories have been developed previously, they have always been done on large satellite platforms, meaning a larger mass that must be sent up into orbit. The benefit of the CubeSat form factor is that the same quality of data can be collected on a platform that is of a smaller mass, meaning a smaller cost to put a Thermospheric winds laboratory into orbit, making the CubeSat a more appealing choice economically. Although the smaller size of the satellite is convenient, it also comes with some challenges. For the etalon to report accurate information, it must be kept in a rigidly controlled thermal environment despite the constantly changing ambient conditions. This problem is also exaggerated due to the proximity of the etalon with heat emitting electronics systems. To satisfy the temperature requirements of the etalon a new thermal control system compatible with the
small form factor satellite chassis must be developed. By designing a thermal control system to regulate
the internal temperature of the CubeSat, the etalon may be successfully utilized in a small form factor
satellite.

1.2. Project Objectives

Michigan Aerospace provided a project criterion with two goals that must be met. The main goal of
the thermal control system must be to maintain a temperature gradient of 0.1 °C across the etalon. A large
temperature gradient across the etalon may result in distortion of the wavelength of light passing through
the etalon, and an inaccurate image may form as a result. The secondary goal is for the detector to be
cooled to a sufficiently low temperature, ideally 0 °C. A detector that is not sufficiently cooled will
produce dark current, causing false readings and inaccurate data.

The goal of the team is to meet the requirements set by Michigan Aerospace using both active and
passive means of thermal control. To determine the correct amount of thermal control that must be
utilized, the group will assess the likely orbital parameters that the satellite will have, as well as the orbit
of the Earth around the Sun. Information about the magnitude of radiation heat transfer incurred during
the orbit can be calculated from these known orbital parameters and “hot” and “cold” cases for the
satellite will be developed from the orbital data. The values calculated from the radiation heat transfer
will then be set as boundary conditions for internal thermal simulations. These internal simulations are
where the thermal control system will be developed using an iterative method.

1.3. Design Constraints

The design of a thermal control system for use in a small form factor satellite can pose a unique
challenge that results in a more constrained design than a typical thermal control system. When designing
in a small form factor satellite there are a few main caveats to remember. The most obvious constraint is
the lack of internal space within the satellite bus. The satellite is planned to be built off a 6U satellite bus,
meaning the internal volume of the satellite will be a maximum of 60cm³. Considering that a significant
portion of the internal volume must be filled with essential components, the maximum available volume for an additional thermal control system can be expected to be < 40cm³.

In addition to the limited design space, it is also important to remember that some traditional methods of heat management will not work in an LEO environment. Due to the limited atmosphere in LEO heat transfer through convection will not work, meaning heat management devices such as fans cannot be used to cool the internal components. The other two primary methods of heat transfer, radiation, and conduction, must be utilized instead. There are both active and passive methods of using radiation and conduction to move heat and the pros and cons of both should be carefully considered.

*Image 1.1: Reference Scale of 6U Satellite*
Image 1.2: Satellite Internal Components

Image 1.3: Full Satellite View w/ Removed Side Panel
1.4. Satellite Orientation

A Local Vertical/Local Horizontal (LVLH) attitude reference frame is used for the CubeSat. The Z-axis, the Local Vertical, points in the nadir direction, where the nadir at a given point is defined as pointing in the direction of the force of gravity. In the case of an orbiting satellite, the nadir vector will point from the bottom of the satellite towards the center of the Earth. The Y-axis, the Local Horizontal, is orthogonal to the orbital plane and points along the direction of the station angular momentum in its orbit. The X-axis, the Velocity Direction, is tangent to the orbital plane and is aligned with the satellite’s direction of motion, completing the reference frame.

Image 1.4: LVLH Attitude Reference Frame
The 2U face of the CubeSat with parallel extended solar panels will face in the -Z direction, away from the Earth. The first extended telescope baffle, referenced as “green field of vision (FOV) 1,” is located on a 3U face. This face is offset 315° from the positive X-axis, in the direction of motion. The second extended telescope baffle, referenced as “red FOV 2,” is located on a 6U face. This face is offset...
225° from the positive X-axis. To simplify calculations and achieve maximum and minimum temperatures on select surfaces, the orientation of FOV 1 and FOV 2 were rotated to align with the +X and +Y axes, respectively.

Image 1.5: Orthogonal View of the CubeSat Orientation in the LVLH Attitude Reference Frame, Featuring FOV 1 and 2
1.5. Altitude and Orbital Elements

The LEO region of the Earth considers the area of space below an altitude $h \cong 2000 \text{ km}$, although most Earth-observing satellites operate between altitudes of $h = [400, 800] \text{ km}$. For initial thermal simulations, Michigan Aerospace recommended an altitude of $h = 600 \text{ km}$.

A Keplerian orbit is described by six primary elements, the eccentricity $e$, semimajor axis $a$, inclination $i$, right ascension of the ascending node $\Omega$, argument of periapsis $\omega$, and true anomaly $v$. For a circular Earth orbit, the eccentricity is approximated as $e = 0$, where the semimajor axis is equal to the diameter of the orbit. For this orbit, the semimajor axis is approximated as $a = 2(R_e + h) = 2(6378 + 600) = 13956 \text{ km}$. The argument of periapsis is $\omega = 0$, as the angle between the ascending node and periapsis does not truly exist in a circular orbit. The true anomaly is the angle between the orbiting body and direction of periapsis at a given time and will be $v_0 = 0$ at the beginning of the orbit.
Upon Michigan Aerospace’s request, only two orbital inclinations $i$ were considered to keep the thermal fluctuation manageable. The first, a low inclination orbit, maintains an inclination $i_{LI} \leq 20^\circ$ and is primarily used for equatorial studies that focus on the tropics. The second, a sun-synchronous orbit, typically uses an inclination $i_{SO} = 98^\circ$, allowing for nearly global coverage while maintaining the angle of sunlight on the surface of the Earth. The orbital plane of the satellite rotates roughly $1^\circ$ eastward each day to move with the Earth’s movement around the Sun. Thus, the satellite will always cross the equator at the same local mean solar time. To achieve Michigan Aerospace’s recommended local mean solar time of 9AM, the right ascension of the ascending node is chosen as $\Omega_{SS} = 135^\circ$.

*Image 1.7: 3D View of a 6-Period Low Inclination Orbit at Specified Conditions*
Image 1.8: 2D View of a 6-Period Low Inclination Orbit at Specified Conditions

Image 1.9: 3D View of a 6-Period Sun-Synchronous Orbit at Specified Conditions
2. Satellite Systems

When implementing a new system into the satellite, it is important to consider how the new system will impact the other systems. The subsystems of the satellite can be divided into a few distinct parts. The structure subsystem consists of primarily the satellite bus, which houses all of the internal components of the satellite and dictates the maximum size of what can be placed within the satellite. The electronic subsystem describes both the energy generation and consumption of the satellite and their limits. In this case the electronic subsystem is based off of the system that comes with the satellite bus. The optical subsystem is a system that is specific to this satellite and its intended mission. Since the information gathered by this satellite relies heavily on optical data, interference with that system should be kept to a minimum. Other systems like communications and flight maneuvering systems can also be considered, but those are less relevant to the scope of the design project.
2.1. Structure Subsystem

The CubeSat will be based around the Blue Canyon XB6 bus. The XB6 is a 6U class CubeSat bus suitable for operation in LEO and geostationary orbit (GEO). It is notable that this satellite bus comes with its own electronics control unit which governs the energy storage, production, and output.

<table>
<thead>
<tr>
<th>Blue Canyon XB6</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>6U</td>
</tr>
<tr>
<td>Available Payload Volume</td>
<td>4U</td>
</tr>
<tr>
<td>Chassis</td>
<td>Aluminum 6061</td>
</tr>
<tr>
<td>System Bus Voltage</td>
<td>9 - 23V (battery and array dependent)</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>75 – 185Wh</td>
</tr>
<tr>
<td>Solar Panels</td>
<td>118W</td>
</tr>
<tr>
<td>High Current Capability</td>
<td>Unregulated up to 140W</td>
</tr>
<tr>
<td>XACT – Bus Nominal Power</td>
<td>&lt; 6.3W (Excluding RF Comm)</td>
</tr>
<tr>
<td>Mass / Volume for Avionics</td>
<td>1.5kg / 10cm x 10 cm x 14cm</td>
</tr>
<tr>
<td>Orbit Altitude / Orbit Lifetime</td>
<td>LEO &gt; 5 Years</td>
</tr>
</tbody>
</table>

*Table 2.1: Blue Canyon XB6 Specifications*

2.2. Electronic Subsystem

The electronic subsystem of the CubeSat is comprised of the primary components that are included with the XB6 bus as well as the instruments required to gather data for the mission. From the specifications provided by Blue Canyon, the bus nominal power excluding RF communications is less than 6.3W, and the solar panels can provide up to 118W.

In order to facilitate the gathering of data other electrical components must be included in the electrical system. Michigan Aerospace provided a preliminary bill of materials regarding additional electrical components that must be added to the CubeSat for data collection.
<table>
<thead>
<tr>
<th>Device</th>
<th>Power Consumption (W)</th>
<th>Duty Cycle</th>
<th>Average Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>3.6</td>
<td>100%</td>
<td>3.6</td>
</tr>
<tr>
<td>Neon Calibration Lamp</td>
<td>0.1</td>
<td>1%</td>
<td>0.001</td>
</tr>
<tr>
<td>White Calibration Lamp</td>
<td>0.5</td>
<td>1%</td>
<td>0.001</td>
</tr>
<tr>
<td>Scan Motors (x2)</td>
<td>15</td>
<td>10%</td>
<td>1.5</td>
</tr>
<tr>
<td>Shutter</td>
<td>20</td>
<td>1%</td>
<td>0.2</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>5</td>
<td>100%</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>&gt; 10.3</strong></td>
</tr>
</tbody>
</table>

*Table 2.2: Specifications of Additional Electronics*

In Table 2.2, the total power consumption of the additional electrical components added by MA should be slightly more than 10.3W. In total, the nominal power consumption of the satellite is at 16.6W without a thermal control system. By knowing the total power capacity, the total nominal power consumption, the margin of remaining power can be determined. Preferably the power consumed by the thermal control system should be smaller than this margin.

### 2.3. Optical Subsystem

The mission of this satellite in particular means that the tools used for gathering data should also be considered. A system of optical lenses, detectors, and mirrors will be used to relay information onto an imaging plane where the data will become ready for analysis. The main component of the optical subsystem is the etalon, which must be carefully maintained within a small range of temperatures. Another critical component of the optical subsystem is the detector, where it must be cooled to below 0 °C. A properly working thermal control system will be able to reduce the temperature on the detector to sub-zero levels while managing the thermal gradient on the etalon to stay within its required temperatures. Another critical aspect of the optical system is the line of sight between the telescope boresights and the detector. Information from the telescopes must be unobstructed on its path to the
detector, so it is imperative that no physical obstruction exists on the path that the information will take from the telescope to the detector.

3. Thermal Control Systems

3.1. Power, Weight, Volume, and Cost Considerations

The CubeSat used for this mission is a Blue Canyon XB6, a 6U class with an orbit lifetime of at least 5 years for LEO and 2 years for GEO. A single CubeSat unit houses a total volume of 1000 cm$^3$ (0.001 m$^3$), with this small size reducing deployment costs and enabling the launch of multiple satellites at a time. While these advantages prove useful to academic research and commercial missions necessitating satellite constellations, the CubeSat’s functionality is also drastically reduced.

The 6U class is limited to a typical available payload volume of 4U, heavily restricting the number of instruments and thermal control methods that can be used. Considering the instruments Michigan Aerospace needs to support their interferometer, the available payload volume is further reduced, limiting the possible configurations. Similarly, the onboard power available is limited, as the CubeSat will spend time out of direct sunlight and will not be able to consistently use the solar panels to store energy. The total weight of the CubeSat and overall component costs also factor into which thermal control methods can be compiled for the final assembly. Exceeding limitations in either category could increase launch difficulty and overall project cost, defeating a CubeSat’s advantage of providing a relatively inexpensive platform.

3.2. Exploration of Thermal Control Methods

Historically, there are many varying methods of thermal control that have been implemented upon satellites, with different combinations creating a cohesive and complementary system. Each method provides its own advantages and disadvantages, primarily considering power consumption, payload volume, and added weight. A single form of thermal control would be inadequate to provide the
temperature gradient required for the mission, therefore multiple forms and combinations will be considered for the final system.

When considering power consumption, thermal control methods are differentiated into active and passive forms. The former requires a source of power to operate, while the latter provides thermal control independently. Passive methods are useful as initial steps to limit the temperature fluctuation a satellite will endure, although there is little ability to make specific temperature adjustments. While active methods consume power – often limited on a satellite – their inclusion is necessary to adjust for a strict temperature gradient.

3.2.1. Thermal Washers

Thermal washers, also known as insulating washers, are washers that have a very low thermal conductivity. Thermal washers provide a cost-effective passive form of thermal isolation to the internal packaging of the CubeSat. The attractive aspect of thermal washers is the small footprint, weight, and practicality. Due to the material and size the washers are lightweight and practical for all mounting purposes on the CubeSat.

The washers decided on and designed are made of the material PEEK, polyether ether ketone, a low thermal conductivity material that is commonly used for thermal washers. The thickness ranges from manufactures, the range that was decided on was between 0.03-0.09 inches, with the most used being the 0.09 in washer. The goal of using thermal washers is to prevent the walls of the CubeSat from conducting heat and causing the walls to radiate the heat back into the CubeSat.
### Table 3.1: Thermal Properties of Thermal vs. Conventional Washer Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Heat Capacity (J/g-K)</th>
<th>Thermal Conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyetheretherketone (PEEK)</td>
<td>1.40 – 1.70</td>
<td>0.17 – 0.95</td>
</tr>
<tr>
<td>Mica</td>
<td>0.88</td>
<td>0.30 – 0.70</td>
</tr>
<tr>
<td>AISI 4140 Steel</td>
<td>0.47</td>
<td>42.6</td>
</tr>
<tr>
<td>Aluminum 6061-T6</td>
<td>0.90</td>
<td>167</td>
</tr>
</tbody>
</table>

3.2.2. Thermoelectric Coolers

Thermoelectric coolers are a form of active thermal control for the CubeSat model, providing a cooling effect. The thermoelectric coolers follow the Peltier Effect, which is the transition of n-type, negative thermopower, and p-type, positive thermopower, through a semiconductor material connected to a metallic contact pad. The benefits of the thermoelectric coolers as an active form of thermal control are the thermoelectric cooler consists of no mechanically moving parts and no working fluid. The thermoelectric cooler can change the temperature output depending on the voltage supplied. The sizing of thermoelectric coolers can be a design specification and depend on the manufacturer’s capabilities. Although the thickness of the thermoelectric coolers can be estimated between a range of 1 to 6 millimeters.

Two thermoelectric coolers, Marlow SP1507 and TE-2-(127-127)-1.15 were examined throughout the length of the project. With the Marlow SP1507 being the slightly smaller thermoelectric cooler design utilized in section 5.2, while the TE-2-(127-127)-1.15, the larger thermoelectric cooler, used in section 5.1.
<table>
<thead>
<tr>
<th>Thermoelectric cooler</th>
<th>Marlow SP1507</th>
<th>TE-2-(127-127)-1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Testing Temperatures (K)</strong></td>
<td>300.15 323.15</td>
<td>300.15 323.15</td>
</tr>
<tr>
<td><strong>Maximum Pumped Heat (W)</strong></td>
<td>34 37.3</td>
<td>5.4 6.2</td>
</tr>
<tr>
<td><strong>Maximum Temperature Drop (K)</strong></td>
<td>84 95</td>
<td>64 72</td>
</tr>
<tr>
<td><strong>Maximum Current Strength (A)</strong></td>
<td>5.8 5.8</td>
<td>1.8 1.8</td>
</tr>
<tr>
<td><strong>Maximum Voltage (V)</strong></td>
<td>15.4 17.1</td>
<td>4.7 5.4</td>
</tr>
</tbody>
</table>

*Table 3.2: Comparison between the TE-2-(127-127)-1.15 and Marlow SP1507*

The choice of the Marlow SP1507 provides the simulations with a pre-defined thermoelectric cooler when assigning the thermoelectric cooler in the flow simulations, when the other thermoelectric coolers examined were user-defined in the flow simulations, providing a chance of error. The Marlow is also a single stage thermoelectric cooler compared to the other thermoelectric coolers examined, which multistage can be beneficial for the most cooling per unit, but the tradeoff is that multistage thermoelectric coolers are thicker and take more space, multistage usually need higher voltages and currents to effectively produce the cooling affect also. The Marlow SP1507 provided a low maximum current and a low operating voltage for cooling, as recommended by the manufacturer.

Positives of the TE-2-(127-127)-1.15 consist primarily due the wide range maximum heat pumped. While the negatives of using the TE-2-(127-127)-1.15 come from the size to maximum temperature dropped comparison, with the size being larger than the SP1507 with little difference in the maximum heat dropped. The TE-2-(127-127)-1.15 is also a user-defined thermoelectric cooler in SolidWorks, which can provide errors in the graphical data.

**3.2.3. Patch Heaters**

Patch heaters are commonly utilized in spacecraft when there is a specific temperature needed in some section and passive thermal control is insufficient. These are just one kind of heater that is effective, however this is the kind that was decided on for this project due to the customizability in their design and the robust construction and operational temperature ranges. Patch heaters that are commonly used in
spacecraft are typically composed of one or more circuits, typically composed of nickel, wedged between layers of flexible, electrically insulated material, such as Kapton. Once power is supplied to the heater, the resistive material begins to dissipate that power as heat, typically through conduction. With this choice of material, patch heaters offer a large operational temperature range of around -200°C to 200°C and offer exceptional resistance to solvents, oils, radiation, fungus, and tearing/cuts, making it an ideal choice for utilization on this CubeSat. Combining the customizable pattern of the resistive material inside the patch heater, the low outgassing properties of the Kapton, and simple mounting methods, given the strict temperature gradient of 0.1°C, it was found that this type of heater would be essential in reaching that goal for this CubeSat.

![Kapton Patch Heater](image3.png)

*Image 3.1: Kapton Patch Heater*

Designing the patch heaters to be utilized in the simulations was relatively simple as they were just set to a desired length and width, and were 0.64 mm thick, the typical thickness of patch heaters designed for satellites and spacecraft. Due to the possibility of complex patterns in the resistive material and the added complexity of simulating layered material accurately, the patch heaters were designed as simple
plates for the purposes of this project. Controlling these heaters in practice requires methods of control, such as thermocouples, thermistors, and thermal fuses, and with adequate feedback systems.

3.2.4. False Walls

False walls provide a physical barrier between an object that is desired to be blocked from electronic radiation and the object that is radiating. The thickness and sizing of the false walls are all determined in the detailed design. The material of the false walls is determined to be aluminum 6061, which has a relatively low emissivity coefficient making it suitable for limiting the radiated heat from a body.

Three different false walls were designed and configured in the CubeSat to block heat at the source. One wall is set near the microcontrollers to block the heat generated by the microcontrollers. The other wall near the etalon to block heat from the scan motors, to ensure that the etalon is meeting temperature gradient objective. The last false wall was placed in front of the camera to ensure the heat generated from the scan motors was blocked from radiating to the camera. The false walls are mounted to the walls of the CubeSat using thermal washers to separate the hot plate from the walls of the CubeSat.

3.2.5. Radiators

External radiators were designed to have an external face slightly offset from the face of the external CubeSat wall. Using thermal washers to protect from the radiator surface being in contact with the wall of the CubeSat. The radiator is designed to have a form of external thermal control such as thermal paint or a high emittance material as a surface coating. Underneath the external form of thermal control is a plate of aluminum as the external radiate surface, with an aluminum honeycomb core underneath the aluminum plate. On the internal side of the radiator a basic aluminum plate was initially designed with the desire to have another set of bent aluminum baffles attached to the final plate. Due to the design space limitations the aluminum plate on the internal side of the radiator was eliminated and a bent aluminum sleeve was decided to save space and still provide enough baffle effect. The design of the baffle effect is to limit the radiator from radiating back into the CubeSat. The radiator sums the environmental loads of heat with the transferred internal loads of heat and reradiates the energy. The goal of the radiator is to
conduct heat from some delivery method and dissipate the heat through the external surface out into free space.

![Image of conceptual radiator function]

*Image 3.2: Conceptual Radiator Function*

Two areas designed for the radiator are on the top wall of the CubeSat with a hole being cut in the center, splitting the microcontrollers, the detector and the scan motors. The other design had a smaller hole being cut behind the detector and moving the detector forward away from the wall of the CubeSat. Both designs provided ample room for transporting the heat through the form of heat pipes or heat straps and provided a method for mounting both the delivery method of the heat and the radiator itself.

**3.2.6. Heat Pipes**

Heat pipes are heat-transfer devices that incorporate phase transitioning to transfer heat between two solid materials. Phase transitioning refers to the physical process of a medium transitioning from one state of matter to another (e.g., liquid to gas), and subsequently the heat being absorbed or released during this process. Heat pipes have rigid designs since they utilize solid metal piping that houses some liquid
that carries the heat away from a designated area. Multiple kinds of heat pipes are available depending on the requirements, however there are only a select few that are specifically meant to work in the vacuum of space. Effective heat pipes include constant conductance, variable conductance, loop, and space copper-water heat pipes. For the purpose of the project, constant conductance heat pipes were chosen based on input from Michigan Aerospace, and the effectiveness in transporting heat efficiently by utilizing the latent heat of the working fluid through evaporation and condensation. The model of heat pipes that were utilized were designed rigidly and are designed for specific internal configurations with respect to all internal thermal control devices. The positioning of these pipes is primarily on surfaces that either generate or absorb a large amount of heat, either from conduction or radiation, or on surfaces that need to stay as cold as possible, and then are routed and attached to the radiator. Material choice for the heat pipes is based on a variety of factors, not least of which is the ambient temperature that the CubeSat is expected to experience. This leads to an aluminum piping with a working fluid of ammonia as opposed to copper piping and water as the working fluid. This combination of material and fluid is common in spacecraft thermal control for the lightweight and nonmagnetic nature of aluminum, and the freezing temperature of ammonia being sufficiently low for the ambient temperatures expected.

Heat pipe placement, as mentioned previously, is based on the locations that either absorb the most heat or are needed to be kept relatively cold. Other placement options vary based on the placement of the radiator and other internal thermal control components.

3.2.7. Thermal Paint

Thermal paint is a form of passive thermal control which can be used on both the exterior and interior of a satellite. Thermal paint is lightweight and takes up minimal volume, providing a well-rounded solution to the satellite’s thermal control requirements. Thermal paint is characterized by its emissivity $\varepsilon$ and absorptance $\alpha$. Emissivity is the unitless measure of a material’s effectiveness in emitting thermal radiation. A high emissivity is commonly used on the exterior of a satellite to reflect high amounts of incoming radiation. Absorptance measures the opposite, the effectiveness of a material’s ability in
absorbing radiant energy. A lower value would be more desirable for the exterior of a satellite, so unnecessary energy does not increase the temperature of the satellite drastically. Thermal paint is commonly used for spacecraft applications, although its effectiveness can decrease when applied to smaller surface areas. Different thermal paints can be used in patterns to achieve various results, such as dotting or striping. For simplicity within simulations, only one thermal paint was evaluated at a time, covering the entirety of the CubeSat’s available surface area.

AZ-93 white thermal paint from AZ Technology is used for temperature simulations of the CubeSat. This inorganic coating has an emittance of $\varepsilon_{AZ-93} = 0.91 \pm 0.02$ and an absorptance of $\alpha_{AZ-93} = 0.15 \pm 0.02$.

4. Thermal Analysis

4.1. Earth Orbital Parameters

The orbit of the Earth around the Sun plays a large role in the overall temperature environment that the satellite will experience. The Earth is known to have a slightly eccentric orbit around the Sun ($e_{Earth} = 0.0167$) which implies that at some point in the orbit the Earth will be at a maximum and minimum distance from the Sun. These are known as aphelion and perihelion, respectively. If the magnitude of the orbit semi-major axis ($a_{Earth} = 1.496 \times 10^8$ km) and eccentricity is known, the distance between the Earth and Sun can be determined for a given true anomaly. The true anomaly is the angular position of the Earth in relation to the Sun.

$$r(v) = \frac{a(1-e^2)}{1+e \cos(v)}$$  \hspace{1cm} (4.1.1)

The true anomaly at perihelion is 0 and $\pi$ at aphelion. Knowing the true anomaly at these points means that the minimum and maximum distances between the Earth and Sun can be calculated.

$$r_p(0) = \frac{a(1-e^2)}{1+e \cos(0)} = 1.471 \times 10^8 \text{ km}$$  \hspace{1cm} (4.1.2)

$$r_A(\pi) = \frac{a(1-e^2)}{1+e \cos(\pi)} = 1.521 \times 10^8 \text{ km}$$  \hspace{1cm} (4.1.3)
Determining the value of perihelion and aphelion is particularly important when it comes to determining the minimum and maximum intensity of the solar flux that the Earth and satellite will experience. Knowing the true anomaly of Earth at any given moment means that the distance between the Earth and Sun, and therefore the magnitude of solar flux, can be found at any point in the Earth’s orbit.

4.2. Satellite Heat Transfer

As a general definition, heat is defined as the form of energy that is transferred from one system to another, as the result of a temperature difference. Heat will always move from the high temperature system to the low temperature system until thermal equilibrium is achieved, and is transferred through three different modes: conduction, convection, and radiation.

4.2.1. Conduction

Conduction is the transfer of energy through particle interactions, where high energy particles within a substance transfer energy to lower energy particles. The rate of heat conduction through a medium largely depends on its geometry and is considered proportional to the temperature difference across the medium and the heat transfer area but is inversely proportional to the thickness of the medium. Considering this, the rate of heat conduction from point \( i \) to point \( j \) within a medium is mathematically described as:

\[
\dot{Q}_{ij,\text{cond}} = -kA\frac{\Delta T}{L} = kA\frac{T_i - T_j}{L} \tag{4.2.1}
\]

Here, \( k \) is the thermal conductivity of the medium, which represents the measure of the material’s ability to conduct heat and has units of \( \frac{W}{m \cdot K} \). \( A \) is the area of the medium, \( L \) is the distance between points \( i \) and \( j \), and \( T \) is the temperature of points \( i \) and \( j \).

Conduction also occurs between objects with touching surfaces and is characterized by conductance \( C_{\text{cond}} \), with units of \( \frac{W}{K} \). Conductance can be used in place of the term \( \frac{kA}{L} \) to calculate the rate of heat transfer.
conduction, although estimating this parameter is complicated. Contact conductance is determined by many factors, including the size of the area in contact, the materials in contact, the pressure distribution between the surfaces, and other considerations.

### 4.2.2. Convection

Convection is the transfer of energy between a solid and a liquid or gas in close contact and is related to both conduction and fluid motion. The rate of convection heat transfer is expressed through Newton’s law of cooling and is proportional to the temperature difference between points $i$ and $j$, which represent the solid and fluid, respectively.

$$\dot{Q}_{ij\text{conv}} = hA_i \Delta T = hA_i(T_i - T_j)$$  \hspace{1cm} (4.2.2)

The parameter $h$ is the convection heat transfer coefficient with units of $\frac{W}{m^2\cdot K}$. $h$ is not a property of the fluid, but rather an experimentally determined parameter that depends on various influences, similar to those that determine contact conductance. $A_i$ is the surface area of the solid in which convection heat transfer takes place, $T_i$ is the temperature of the solid, and $T_j$ is the temperature of the fluid.

Typically, convection heat transfer is not observed within satellites, as the internal components reside within a vacuum. However, convection is still an important consideration during the launch or orbit insertion phase of the satellite.

### 4.2.3. Radiation

Radiation is the energy emitted by matter via electromagnetic waves, or photons, due to changes in the electronic configurations of atoms or molecules. No intervening medium is necessary for radiation heat transfer, unlike conduction and convection. The CubeSat will receive radiation heat transfer in three different forms. Panels facing the sun will receive direct solar radiation, and panels facing the Earth will receive direct infrared (IR) radiation and reflected albedo radiation from the Earth.
4.2.3.1. Solar Flux

Solar flux is defined as the solar radiation received from the Sun. It is critical to know the solar flux at any given time, as it has a significant impact on the ambient temperature of the satellite. The impact of solar flux can easily be seen on a satellite with a nadir orientation where the nadir (Earth-facing) surface typically has a lower temperature than any other surface on the satellite due to the lack of incoming solar flux. For Earth-orbiting satellite applications, the amount of solar flux absorbed by the satellite is calculated by finding the intensity of solar flux at any point in the Earth’s orbit around the Sun. The energy balance for solar flux is represented by:

\[
(q_{\text{sol}})_r = \frac{\dot{Q}}{4\pi r^2}
\]  \hspace{1cm} (4.2.3)

This represents the solar flux at Earth when it is at distance \( r = 1 \) a.u. from the Sun. Using the conservation of energy, the solar flux at Earth aphelion and perihelion can be calculated:

\[
\dot{Q} = (q_{\text{sol}})_{r=1} 4\pi 1^2 = (q_{\text{sol}})_{r_p} 4\pi r_p^2 = (q_{\text{sol}})_{r_A} 4\pi r_A^2
\]  \hspace{1cm} (4.2.4)

\[
(q_{\text{sol}})_{r_A} = \frac{(q_{\text{sol}})_{r=1}}{r_A^2} = \frac{(q_{\text{sol}})_{r=1}}{(1+e^2)} = 1317 \text{ W/m}^2
\]  \hspace{1cm} (4.2.5)

\[
(q_{\text{sol}})_{r_p} = \frac{(q_{\text{sol}})_{r=1}}{r_p^2} = \frac{(q_{\text{sol}})_{r=1}}{(1-e^2)} = 1419 \text{ W/m}^2
\]  \hspace{1cm} (4.2.6)
Knowing the maximum and minimum solar flux over the period of the orbit an estimation of ‘hot’ and ‘cold’ cases can be determined. Knowing the hot and cold cases gives the thermal control system designers a clear picture of the range of temperatures in which the thermal control system must function reliably.

4.2.3.2. Albedo Flux

In addition to the solar flux, albedo flux has a quantifiable impact on the satellite ambient temperature. Albedo flux is solar energy that is reflected off of the Earth and its atmosphere, and typically has a smaller, but not insignificant, magnitude than solar flux. Unlike solar flux, albedo flux is not measured as originating from a distinct point source but rather as a function of the subtended angle created with the satellite and the surface of the Earth. Since the albedo flux is highly dependent on the angle of the satellite in relation to the Earth, this usually leads to a non-uniform intensity of flux on the satellite surface. Due to the complications brought about by the non-uniform intensity, some assumptions must be made to simplify the albedo flux calculations. The simplified albedo flux model generally finds a value that is slightly lower than the true value due to these assumptions. The simplified model for calculating albedo flux on the nadir facing surface of the satellite is as follows:

$$\left( \dot{q}_{\text{alb}}(\xi) \right)_{\text{nadir}} = \dot{q}_{\text{sol}} \rho \left( \frac{r_e}{r_e+h} \right)^2 \cos(\xi)$$  \hspace{1cm} (4.2.7)

The key variables in this formula are $\xi$ (solar zenith angle), $\rho$ (fraction of sunlight reflected), $h$ (altitude above the planet), and $\dot{q}_{\text{sol}}$ (intensity of the sunlight on the planet).

4.2.3.3. Earth Infrared Flux

The final contribution to the incoming flux on the satellite is the Earth infrared flux. The Earth infrared flux originates from the residual heat of the Earth itself and is a function of the distance between the satellite and its proximity to the body it is orbiting. Like the albedo flux calculations, a simplified model based off of assumptions is used to calculate the Earth infrared flux. For Earth infrared flux calculation, it is assumed that the Earth is at a uniform temperature while also being at thermal radiation.
equilibrium. It is also assumed that the albedo over the surface of the Earth is uniform. Assuming steady state heat transfer the heat balance of the Earth can be defined as:

\[ Q_{in} = Q_{out} \] (4.2.8)

\[ \dot{Q}_{in} = \dot{q}_{sol} A_{proj} (1 - \rho) \] (4.2.9)

\[ \dot{Q}_{out} = 4\pi r_e^2 \varepsilon \sigma T^4 \] (4.2.10)

Knowing the heat that is incoming to Earth, the uniform temperature of the planet can be found:

\[ \dot{q}_{sol} A_{proj} (1 - \rho) = 4\pi r_e^2 \varepsilon \sigma T^4 \] (4.2.11)

\[ T = \sqrt[4]{ \frac{\dot{q}_{sol} (1-\rho)}{4\varepsilon \sigma} } \] (4.2.12)

The flux emitted by the planet is defined by:

\[ \dot{q}_{pla} = \frac{\dot{q}_{sol} (1-\rho)}{4} \] (4.2.13)

\[ (\dot{q}_{pla})_{nadir} = \frac{\dot{q}_{sol} (1-\rho)}{4} \left( \frac{r_e}{r_e+h} \right)^2 \] (4.2.14)

**4.2.3.4. View Factors**

A view factor, represented as \( F_{i\rightarrow j} \), is defined as the proportion of radiation that leaves surface \( i \) and impacts surface \( j \). In the case of a cubic object, including the CubeSat, a 6-by-6 matrix will represent the total amount of view factors.

\[
\begin{bmatrix}
F_{+Z\rightarrow+Z} & F_{+Z\rightarrow-Z} & F_{+Z\rightarrow+X} & F_{+Z\rightarrow+Y} & F_{+Z\rightarrow-X} & F_{+Z\rightarrow-Y} \\
F_{-Z\rightarrow+Z} & F_{-Z\rightarrow-Z} & F_{-Z\rightarrow+X} & F_{-Z\rightarrow+Y} & F_{-Z\rightarrow-X} & F_{-Z\rightarrow-Y} \\
F_{+X\rightarrow+Z} & F_{+X\rightarrow-Z} & F_{+X\rightarrow+X} & F_{+X\rightarrow+Y} & F_{+X\rightarrow-X} & F_{+X\rightarrow-Y} \\
F_{+Y\rightarrow+Z} & F_{+Y\rightarrow-Z} & F_{+Y\rightarrow+X} & F_{+Y\rightarrow+Y} & F_{+Y\rightarrow-X} & F_{+Y\rightarrow-Y} \\
F_{-X\rightarrow+Z} & F_{-X\rightarrow-Z} & F_{-X\rightarrow+X} & F_{-X\rightarrow+Y} & F_{-X\rightarrow-X} & F_{-X\rightarrow-Y} \\
F_{-Y\rightarrow+Z} & F_{-Y\rightarrow-Z} & F_{-Y\rightarrow+X} & F_{-Y\rightarrow+Y} & F_{-Y\rightarrow-X} & F_{-Y\rightarrow-Y}
\end{bmatrix}
\]

Radiation leaving a surface is conserved, therefore the sum of all view factors from any given surface should be equal to one. This can be verified by summation of each row in the matrix, to validate unity.
For a flat surface, there is no way for radiation to leave and impact the surface later, as radiation travels in straight lines. Therefore, the view factor of a self-viewing surface is represented as $F_{i \rightarrow i} = 0$. This behavior defines the view factor matrix as hollow, rendering the trace of the matrix equal to zero.

View factors also obey the reciprocity theorem, where $A_i F_{i \rightarrow j} = A_j F_{j \rightarrow i}$. As long as the view factor of one surface onto another is known, the areas of both surfaces can be used to calculate the remaining view factor. In the case of equal surface areas, as found within the CubeSat, the view factors should be the same.

The view factor from a surface $A_i$ to a surface $A_j$ is calculated with the angles $\theta_i$ and $\theta_j$ between the normal vectors of each surface and the shortest distance between the normal vectors $S_{ij}$.

![Diagram of View Factor Calculation Variables and Arrangement](image)

The general solution for a view factor between two surfaces is given by:

$$F_{i \rightarrow j} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi S_{ij}} dA_j dA_i$$ (4.2.15)

This integral ultimately becomes difficult to solve for more complicated surface arrangements. For simple geometry, like parallel plates or plates with a common edge, previously determined approximations can be used to calculate the view factors.
For two parallel, identical, rectangular plates that are directly across from each other, the view factor between these two plates is given as:

\[ F_{i \rightarrow j} = \frac{2}{\pi XY} \left( \ln \left( \frac{(1+X^2)(1+Y^2)}{1+X^2+Y^2} \right) \right)^{1/2} + X \sqrt{1+Y^2} \tan^{-1} \frac{X}{\sqrt{1+Y^2}} + Y \sqrt{1+X^2} \tan^{-1} \frac{Y}{\sqrt{1+X^2}} - X \tan^{-1} X - Y \tan^{-1} Y \]  

(4.2.16)

In this equation, \( X = \frac{a}{c} \) and \( Y = \frac{b}{c} \), where \( a \) and \( b \) are the width and length of the rectangle, and \( c \) is the distance between the two plates.

Image 4.3: Diagram of View Factor Calculation Variables and Arrangement for Parallel Plates

For two rectangular plates that share a common edge with \( \theta_{ij} = 90^\circ \), the view factor between these two plates is given as:

\[ F_{i \rightarrow j} = \frac{1}{\pi W} \left( W \tan^{-1} \frac{1}{W} + H \tan^{-1} \frac{1}{H} - \sqrt{H^2 + W^2} \tan^{-1} \frac{1}{\sqrt{H^2+W^2}} + \right. 

\left. \frac{1}{4} \ln \left\{ \frac{(1+W^2)(1+H^2)}{1+W^2+H^2} \left[ \frac{W^2(1+W^2+H^2)}{(1+W^2)(W^2+H^2)} \right]^{W^2} \left[ \frac{H^2(1+W^2+H^2)}{(1+H^2)(W^2+H^2)} \right]^{H^2} \right\} \right) \]  

(4.2.17)

In this equation, \( W = \frac{w}{l} \) and \( H = \frac{h}{l} \), where \( w \) and \( h \) are the lengths of either plate independent of each other, and \( l \) is the length of the shared common edge.
Using these calculations and the previously stated assumptions to confirm validity, the view factor matrix of the CubeSat is calculated as:

\[
F = \begin{bmatrix}
0 & 0.0603 & 0.3081 & 0.1617 & 0.3081 & 0.1617 \\
0.0603 & 0 & 0.3081 & 0.1617 & 0.3081 & 0.1617 \\
0.1027 & 0.1027 & 0 & 0.1595 & 0.4756 & 0.1595 \\
0.1078 & 0.1078 & 0.3190 & 0 & 0.3190 & 0.1464 \\
0.1027 & 0.1027 & 0.4756 & 0.1595 & 0 & 0.1595 \\
0.1078 & 0.1078 & 0.3190 & 0.1464 & 0.3190 & 0
\end{bmatrix}
\]

4.2.3.5. **Radiation Surface Exchange**

Considering the rate of heat transfer due to radiation between two surfaces, the analysis of this exchange can become quite complex. The case of reflection complicates the heat transfer analysis, as a radiation beam leaving a surface can be reflected multiple times before being fully absorbed. If two surfaces were to be assumed as black bodies, this issue of reflection could be disregarded. However, this simplification would not properly represent the properties of the CubeSat and would render any findings invalid. Thus, assumptions will be made that the CubeSat consists of opaque, diffuse, and grey surfaces. In short, the surface is nontransparent, emits and reflects radiation independent of direction, and its radiation properties are independent of wavelength. Each surface is considered isothermal, and the incoming and outgoing radiation are uniform over each surface.
The properties absorptivity $\alpha$, emissivity $\varepsilon$, reflectivity $\rho$, and transmissivity $\tau$ of a real surface can be approximated for an opaque, diffuse, and grey surface. Absorptivity, reflectivity, and transmissivity are related as various fractions of incident light that are absorbed, reflected, and transmitted, and are related through:

$$\alpha + \rho + \tau = 1 \quad (4.2.18)$$

However, for an opaque surface, the transmissivity can be assumed as $\tau = 0$. If the surface reaches thermal equilibrium, it can be assumed that the emissivity and absorptivity are equal, $\alpha = \varepsilon$.

Surfaces both emit and reflect radiation, both of which make up the total radiation leaving the surface. The total radiation energy is calculated without regard to its origin, and is described by the radiosity $J$, the total radiation energy leaving a surface per unit time and per unit area, with units of $\frac{W}{m^2}$. The net rate of heat radiation heat transfer to or from a surface $i$ of surface area $A_i$ is expressed as the difference between the radiation leaving surface $i$ and the radiation incident on surface $i$. This is represented mathematically as:

$$\dot{Q}_i = \frac{E_{bi} - J_i}{R_i} \quad (4.2.19)$$

$E_{bi}$ is the blackbody emissive power of a surface $i$, the amount of energy per unit time per unit area, integrated over all wavelengths, and is equal to:

$$E_{bi} = \sigma T_i^4 \quad (4.2.20)$$

Where $\sigma$ is the Steffan-Boltzmann constant and is equal to $5.669 \times 10^{-8} \frac{W}{m^2 K^4}$, and $T_i$ is the temperature of the surface. The numerator $E_{bi} - J_i$ represents a potential difference, as if it were in an electrical circuit, where the net heat flow can be equated to an electrical current. The term $R_i$ is the surface resistance to radiation, and is expressed as:

$$R_i = \frac{1 - \varepsilon_i}{A_i \varepsilon_i} \quad (4.2.21)$$
When considering two opaque, diffuse, grey surfaces $i$ and $j$, radiosity and the view factor between the two surfaces can describe the net rate of radiation heat transfer from $i$ to $j$ as the difference between the radiation leaving surface $i$ that strikes $j$ and the radiation leaving surface $j$ that strikes $i$. Considering the reciprocity relation between view factors, this can be calculated as:

$$\dot{Q}_{i\rightarrow j} = \frac{J_i - J_j}{R_{i\rightarrow j}}$$ (4.2.22)

where $R_{i\rightarrow j}$, the space resistance to radiation, is equal to:

$$R_{i\rightarrow j} = \frac{1}{A_i \bar{F}_{i\rightarrow j}}$$ (4.2.23)

### 4.2.3.6. Radiation Network

When considering the surfaces of the satellite as one large circuit, the radiation network would consist of the space resistor and the individual surface resistors. Imagining the radiation network between surfaces $i$ and $j$, the total resistance of the network is the sum of each resistance, i.e., $R_{\text{total}} = R_i + R_{i\rightarrow j} + R_j$, as if it were in series. Continuing with the circuit analogy, if the net rate of radiation heat transfer is related to a current, its value can be found by dividing the potential difference between surfaces $i$ and $j$ by the total resistance. Mathematically, this is represented as:

$$\dot{Q}_{ij} = \frac{E_{bi} - E_{bj}}{R_{\text{total}}} = \frac{\sigma (T_i^4 - T_j^4)}{\frac{1 - \varepsilon_i}{A_i \varepsilon_i} + \frac{1}{A_j \varepsilon_j} + \frac{1 - \varepsilon_j}{A_{i\rightarrow j} \varepsilon_{i\rightarrow j}}}$$ (4.2.24)

However, since the CubeSat has multiple surfaces in contact, the radiation flow becomes more complex. Although one may be calculating the heat transfer from surface $i$ to surface $j$, the net heat transfer includes amounts of radiation reflected off of surface $j$ from other surfaces, complicating the radiation network. To reflect a system such as that of the CubeSat, a three-surface enclosure can be considered, then expanded to any given number of surfaces. Each surface will have its own surface resistance, then be connected by space resistances. This creates a system where the radiation can follow many different routes, therefore moving away from the resistors-in-series analogy presented before.
Image 4.5: Diagram of a Three-Surface Radiation Network

Considering this, the radiation system can be broken down into a system of three equations:

\[
\frac{E_{b1} - J_i}{R_i} + \frac{J_i - J_j}{R_{i\rightarrow j}} + \frac{J_k - J_i}{R_{i\rightarrow k}} = 0 \tag{4.2.25}
\]

\[
\frac{J_i - J_j}{R_{i\rightarrow j}} + \frac{E_{b2} - J_j}{R_j} + \frac{J_k - J_j}{R_{j\rightarrow k}} = 0 \tag{4.2.26}
\]

\[
\frac{J_i - J_k}{R_{i\rightarrow k}} + \frac{J_j - J_k}{R_{j\rightarrow k}} + \frac{E_{b3} - J_k}{R_k} = 0 \tag{4.2.27}
\]

The three blackbody emissive powers, also called end point potentials, are known if an initial surface temperature is given. With this information, the radiosities at each node can be solved for, as the net radiation heat transfer at each node should be equal to zero, as it behaves like a current.

Upon solving the radiosities, the net radiation heat transfer of each surface can be calculated as:

\[
\dot{Q}_i = \frac{J_l - J_j}{R_{i\rightarrow j}} + \frac{J_k - J_i}{R_{i\rightarrow k}} \tag{4.2.28}
\]

\[
\dot{Q}_j = \frac{J_l - J_i}{R_{i\rightarrow j}} + \frac{J_k - J_j}{R_{j\rightarrow k}} \tag{4.2.29}
\]

\[
\dot{Q}_k = \frac{J_k - J_i}{R_{i\rightarrow k}} + \frac{J_k - J_j}{R_{j\rightarrow k}} \tag{4.2.30}
\]
When generalizing for multiple surfaces, as is used for the analysis of the CubeSat, this form can be restructured as a matrix and solved for each surface radiosity. This radiation system is written as:

\[ \frac{E_{bi}}{R_i} + \sum_{j=1}^{n} \frac{J_j - J_i}{R_{i-j}} = 0 \]  

(4.2.31)

Similarly, the net radiation heat transfer system can be rewritten and generalized as:

\[ \dot{Q}_i = \sum_{j=1}^{n} \frac{J_j - J_i}{R_{i-j}} \]  

(4.2.32)

### 4.3. Ambient Satellite Temperature

To calculate the changing temperature of the satellite, calculations are broken down per surface or per node. Each node is defined with a temperature and thermal capacity, and a node’s properties are considered at a single point. However, this point will represent the average for the entire surface. A finer mesh of nodes will result in a more accurate and descriptive analysis; however, this greatly complicates the radiation network and model. Therefore, the simplest thermal analysis renders each surface or panel of the satellite as a node. Each node will be modeled as a diffuse node, with a finite thermal capacitance. The heat flow through a diffusion node can be described as:

\[ \Sigma \dot{Q} = \frac{C \Delta T}{t} \]  

(4.3.1)

Where the net heat flux \( \Sigma \dot{Q} \) through the node is a result of the capacitance \( C \), change in temperature \( \Delta T \), and time \( t \). Each node will be connected to adjacent nodes through conductors, which can represent the conduction between two objects with touching surfaces or the convection or radiation between two different surfaces.

To solve for the increase in temperature of each node throughout a defined timestep, the Finite Difference Method is used. This method uses the Taylor Series Expansion of a function, combining the various methods of heat flow to determine the change in temperature. While initially only considering the system of a one-dimensional object only affected by conduction, the second partial derivative of
temperature with respect to space can be related to the partial derivative of temperature with respect to time. Then, after breaking down the one-dimensional object present into multiple nodes of various increment sizes, the equation can be modified with the volume of the node, the conductive resistance, and thermal capacity. This equation can be further generalized beyond a single dimension and can be applied to any node or surface \( i \) in contact with another node or surface \( j \). While this original differentiation only applied to conduction, it can be expanded to the other forms of heat transfer, including any heat generated by internal components. This equation, after the modifications mentioned, becomes:

\[
T_i' = T_i + \frac{\Delta t}{C_i} \left( \sum_j Q_{ij,\text{cond}} + \sum_j Q_{ij,\text{conv}} + \sum_j Q_{ij,\text{rad}} + Q_{i,\text{int}} \right)
\]

(4.3.2)

So, with an initial temperature assumption for each node, such as room temperature upon launch, the net heat flow can be calculated for each node, then used to adjust the temperature after a time step.

### 4.4. Hot and Cold Cases

When launching a satellite, the details of its orbital environment cannot be precisely determined. Both external and internal heat loads will fluctuate during a satellite’s orbit, varying due to the orbit itself, the time the satellite was launched, atmospheric conditions, and other changing factors. To ensure that a satellite can survive its course, designers often choose to simulate hot and cold cases. These cases ensure that, while the precise conditions cannot be estimated, the satellite and its components can survive the most severe conditions it would endure.

Common parameters to change when determining these cases are the solar vector \( S \) and the albedo factor \( A_f \). The solar vector hot case would occur when the Earth is closest to the Sun, whereas the cold case condition is where the Earth is farthest away from the Sun. The albedo factor hot case occurs when increased amounts of radiation are reflected towards the satellite, commonly due to increased cloud cover or ice and snow. The opposite cold case occurs when wide areas of forest or open water can be viewed from space, which absorb more radiation and reflect less towards the satellite.
To simulate the hot case, when the Earth is closest to the sun and radiation is highly reflected by the Earth, a solar vector of $S_{\text{Hot}} = 1419 \frac{W}{m^2}$ and an albedo factor of $A_{f_{\text{Hot}}} = 0.55$ are chosen.

To simulate the cold case, when the Earth is farthest from the sun and radiation is primarily absorbed by the Earth, a solar vector of $S_{\text{Cold}} = 1317 \frac{W}{m^2}$ and an albedo factor of $A_{f_{\text{Cold}}} = 0.18$ are chosen.

4.5. SatTherm Thermal Analysis

Initially, SolidWorks was utilized to simulate both the internal heat generation from the electronics and the external heat generation from the atmosphere for the CubeSat. However, after encountering failed simulations and reviewing previously written academic papers experiencing the same issues, SolidWorks was deemed unfit to complete the external heat transfer simulations. SolidWorks is limited to an altitude of 100 km for simulations, rendering it difficult to accurately assess the external heat transfer at the CubeSat’s orbital altitude of 600 km. Due to software licensing limitations, the MATLAB-based program SatTherm was chosen to simulate the atmospheric heat transfer.

SatTherm was designed in 2009 by San Jose State University in collaboration with NASA’s Ames Mission Design Center and is modeled after Thermal Desktop, able to produce similar results within 4 °C or less. This software calculates the heat transfer for a limited set of nodes, producing a simple thermal model for a small spacecraft. Utilizing the finite difference method to solve for the non-steady temperature of various spacecraft components, the results found by SatTherm are the average temperatures for the individual nodes. The 6U CubeSat was simulated with six nodes, to calculate the average temperature of each surface as it moves throughout the CubeSat’s orbit. The position of the Sun was estimated for the date April 18th, 2023. Each node is named with the format ABC, where A is the panel’s surface area in number of units, B is the positive or negative direction, and C is the panel’s axis. For example, the bottom panel of the satellite facing the Earth is named 2PZ, as it has a surface area of two units and faces in the positive Z direction. Each simulation is run for a total of six hours, with
simulations of 24 hours, albeit with smaller timesteps, run to validate the long-term stability of the satellite’s temperature fluctuation.

4.5.1. Validation of Multi-Period Temperature Stability

While moving through orbit, it is important to determine whether the temperature difference of the satellite would fluctuate with each period, or whether the same maximum and minimum temperatures would be achieved. Both orbit types were simulated for 24 hours without a thermal coating to ensure that the satellite reached a consistent temperature fluctuation. Both orbit types displayed sufficient stabilization of their temperature ranges after the third complete period. It is critical for the satellite to maintain this long-term stability, so the thermal control system can be designed with these maximum and minimum temperatures in mind.

![Figure 4.1: 24-Hour Temperature Analysis of a Sun-Synchronous Orbit with no Thermal Paint](image-url)
Figure 4.2: 24-Hour Temperature Analysis of a Low Inclination Orbit with no Thermal Paint
4.5.2. Analysis without Thermal Paint

The CubeSat was initially analyzed without any thermal paint or coating, assuming the thermal properties of aluminum with an emissivity of $\varepsilon = 0.59$ and an absorptivity of $\alpha = 0.51$.

4.5.2.1. Sun-Synchronous Orbit – Hot Case

The sun-synchronous orbit hot case endures a maximum temperature around 293 K and a minimum temperature around 249 K, as shown in Figure 4.8. Spikes in heat flux are observed in Figures 4.9 a-f, as the satellite moves in and out of direct sunlight.

![Figure 4.3: Temperature Change across Surfaces of a 6U CubeSat for a Hot Case Sun-Synchronous Orbit with no Thermal Paint.](image)
Figure 4.4a-f: Heat Flux Across Surfaces of a 6U CubeSat for a Hot Case Sun-
Synchronous Orbit with no Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ,
2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.2.2. Sun-Synchronous Orbit – Cold Case

The sun-synchronous orbit cold case reaches a maximum temperature around 283 K and a minimum temperature around 245 K, as seen in Figure 4.10. As expected, lower temperatures are reached when compared to the hot case. Similar spikes in heat flux are observed in Figures 4.11 a-f, although not with the same severity as previously observed.

*Figure 4.5: Temperature Change across Surfaces of a 6U CubeSat for a Cold Case Sun-Synchronous Orbit with no Thermal Paint.*
Figure 4.6a-f: Heat Flux across Surfaces of a 6U CubeSat for a Cold Case Sun-Synchronous Orbit with no Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.2.3. **Low Inclination Orbit – Hot Case**

The low inclination orbit hot case reaches a maximum temperature around 306 K and a minimum temperature around 239 K, shown in Figure 4.12. A slightly warmer maximum temperature is reached than that achieved in the sun-synchronous orbit, an expected change since the low inclination spends more time at the equator, in direct sunlight. Different heat flux patterns are observed in comparison to the sun-synchronous orbit, with panel 3NY in Figure 4.13d achieving much lower values than before.

![Figure 4.7: Temperature Change across Surfaces of a 6U CubeSat for a Hot Case Low Inclination Orbit with no Thermal Paint.](image-url)
Figure 4.8a-f: Heat Flux across Surfaces of a 6U CubeSat for a Hot Case Low Inclination Orbit with no Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.2.4. Low Inclination Orbit – Cold Case

The low inclination orbit cold case reaches a maximum temperature around 290 K and a minimum temperature around 235 K, observed in Figure 4.14. Although the equator typically sees more sunlight, and therefore more radiation, a lower temperature is achieved than that in the sun-synchronous orbit. Similar heat flux patterns are observed through Figures 4.15 a-f, although the values are lower when compared to the hot case.

Figure 4.9: Temperature Change across Surfaces of a 6U CubeSat for a Cold Case Low Inclination Orbit with no Thermal Paint.
Figure 4.10a-f: Heat Flux across Surfaces of a 6U CubeSat for a Cold Case Low Inclination Orbit with no Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.3. Analysis with AZ-93 Thermal Paint

Once the CubeSat was analyzed without any thermal coatings, various thermal paints could be applied to the CubeSat's exterior by changing the emissivity and absorptivity properties in SatTherm. A thermal paint with a high emissivity and lower absorptivity will be needed to minimize the amount of temperature fluctuation the satellite observes. As mentioned in Section 3.3.7., the thermal paint AZ-93 is a white, inorganic coat, with an emissivity of $\varepsilon = 0.91 \pm 0.02$ and an absorptivity of $\alpha = 0.15 \pm 0.02$.

4.5.3.1. Sun-Synchronous Orbit – Hot Case

The sun-synchronous orbit hot case with AZ-93 reaches a maximum temperature around 219 K and a minimum temperature around 203 K, seen in Figure 4.16. The temperature drops after insertion and settles into a consistent pattern after the third hour. Considerably lower heat flux patterns are observed in Figures 4.17 a-f. However, the same patterns across the surfaces are maintained.

![Figure 4.11: Temperature Change across Surfaces of a 6U CubeSat for a Hot Case Sun-Synchronous Orbit with AZ-93 Thermal Paint.](image)
Figure 4.12a-f: Heat Flux across Surfaces of a 6U CubeSat for a Hot Case Sun-Synchronous Orbit with AZ-93 Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.3.2. **Sun-Synchronous Orbit – Cold Case**

The sun-synchronous orbit cold case with AZ-93 reaches a maximum temperature around 214 K and a minimum temperature just under 200 K, shown in Figure 4.18. The satellite maintains temperature stability after the third hour. Similar heat flux patterns to the hot case can be seen in Figures 4.19 a-f, although with less severe spiking.

![Figure 4.13: Temperature Change across Surfaces of a 6U CubeSat for a Cold Case Sun-Synchronous Orbit with AZ-93 Thermal Paint.](image)
Figure 4.14a-f: Heat Flux across Surfaces of a 6U CubeSat for a Cold Case Sun-Synchronous Orbit with AZ-93 Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.3.3. Low Inclination Orbit – Hot Case

The low inclination orbit hot case with AZ-93 attains a maximum temperature around 221 K and a minimum temperature around 199 K, shown in Figure 4.20. Compared to the results found without thermal paint, a very similar temperature range is achieved to that of the sun-synchronous orbit. Panel 3NY has a different heat flux pattern as compared to the sun-synchronous results, although maintaining the pattern seen from the simulations without thermal paint. The other panels, shown in Figure 4.21 a-f, are relatively similar to the results previously seen.

![Figure 4.15: Temperature Change across Surfaces of a 6U CubeSat for a Hot Case Low Inclination Orbit with AZ-93 Thermal Paint.](image-url)
Figure 4.16a-f: Heat Flux across Surfaces of a 6U CubeSat for a Hot Case Low Inclination Orbit with AZ-93 Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.3.4. **Low Inclination Orbit – Cold Case**

The low inclination orbit cold case with AZ-93 reaches a maximum temperature around 218 K and a minimum temperature around 196 K, seen in Figure 4.22. The thermal paint closely maintains the temperature range seen in the sun-synchronous simulations and the low inclination hot case. Although the values are lower, the heat flux patterns shown in Figure 4.23 a-f remain similar to those observed in the hot case simulation.

*Figure 4.17: Temperature Change across Surfaces of a 6U CubeSat for a Cold Case Low Inclination Orbit with AZ-93 Thermal Paint.*
Figure 4.18a-f: Heat Flux across Surfaces of a 6U CubeSat for a Cold Case Low Inclination Orbit with AZ-93 Thermal Paint. Starting Clockwise from Upper Left: Panel 2PZ, 2NZ, 3PY, 3NY, 6NX, 6PX.
4.5.4. Final Temperature Results

With AZ-93 thermal paint applied, both the sun-synchronous and low inclination orbits can reach similar temperature ranges that will be maintained throughout orbit. The CubeSat can expect to reach a maximum temperature of 222.786 K in the hot case, and a minimum temperature of 196.495 K in the cold case. With these extrema determined, the internal thermal control configuration can be arranged to maintain the desired temperatures for the onboard instruments.

4.6. Internal Thermal Simulation

4.6.1. Input Parameters and Assumptions

SolidWorks provides plentiful variability when creating flow simulations and defining boundaries and input parameters. After testing different boundary conditions and input parameters, a streamlined process for setting up simulations was produced. Starting in the SolidWorks Flow Simulations tab, the “Wizard” was opened, as seen in Image 4.6 below.

![Image 4.6: Flow Simulation Set-up Part 1](image)

Once the simulation wizard is opened, a name for the simulation is selected, specifying the changing conditions in order to have distinction between every simulation. In the next portion of the wizard, the SI unit system was selected as shown in Image 4.8. The selection of the unit system is arbitrary, but given previous coursework, the SI system provided results and units that were the most familiar, leading to more efficient understanding of the thermal interactions of every component.
Image 4.7: Flow Simulation Set-up Part 2

Image 4.8: Flow Simulation Set-up Part 3
After going to the next portion of the wizard, the analysis type chosen for these simulations is “External”, shown in Image 4.9, which specifies that the simulation should have interactions from external entities. This prevents a closed system from being simulated and allows for heat to dissipate through radiation into the external environment. Next, fluid flow, conduction, and radiation are turned on with the environment temperature being specified to be the ambient temperature at altitude, specified in Image 4.9.

![Image 4.9: Flow Simulation Set-up Part 4](image)

In the next section, the default fluid is chosen for the simulations, which is specified to be a user-defined fluid (gas) at an altitude of 600 km as shown in Image 4.10. The process in which the thermal properties for this gas mixture was determined is outlined later in this section. This default fluid distinguishes the material properties for the ambient environment to allow for more accurate and reliable thermal interactions between physical objects through radiation and convection. While the CubeSat would be in space traveling at a set speed, there is no velocity set for the fluid due to the very low density and pressure expected at 600 km.
Then, the section outlined in Image 4.11 specifies the default solid as Aluminum 6061 since that is one of the most common alloys of aluminum utilized in spacecraft, specifically satellites. Aluminum was chosen as the default solid because not all parts had a material specified due to possible uncertainties. Selecting a default solid essentially sets every part that does not have a defined material to that specific solid, which was the case for the CubeSat chassis and the etalon model.
Image 4.11: Flow Simulation Set-up Part 6

Image 4.12: Flow Simulation Set-up Part 7
For the wall conditions shown in Image 4.12, there are no changes to the default wall radiative surface or roughness options. This allows for all the heat that is emitted through radiation and convection into the ambient environment to be “absorbed” by the computational domain, the volume selected in which the thermal simulations are performed. Having a blackbody wall ensures that no heat will be radiated back onto the external portion of the CubeSat during simulations, making the simulation more accurate as if the satellite was in orbit with almost no obstacles within close proximity for heat to radiate back onto the CubeSat.

Image 4.13: Flow Simulation Set-up Part 8

In the last section of the set-up wizard, thermodynamic parameters were set to simulate the CubeSat as accurately as possible in orbit. At the discretion of Michigan Aerospace, the main parameter was set to “Altitude” with a value of 100 km, the highest altitude SolidWorks supports. Choosing the desired altitude sets the pressure and ambient temperature to a specific value, with only the temperature being able to change through the “Temperature deviation” option. This option was employed to test a temperature range that emulated the suspected hot and cold case temperature differences before the SatTherm code was finalized. In the case of the initial solid temperatures, this value is set to equal the
environment temperature, which includes the desired deviation. Once that temperature is known, the environment temperature from the section shown in Image 4.10 is also set to the final temperature after any deviation. This produces a simulation that starts all objects and the environment at a uniform temperature to allow for an appropriately converging simulation.

Image 4.14: Simulation Input Data Part 1

Once the project is set up, the next step is getting the input data correct to ensure accurate and reliable results. The first step in this process is selecting any solid materials that were previously not selected for specific parts. For this project, the microcontrollers were selected and defined as being the pre-defined, non-isotropic material of an 8-layer PCB for reasons outlined later in this section. This is the only part selected for a unique solid material since everything has either been defined in part files or will be defined by the default solid material set in Image 4.11.
Next, choosing volumetric heat sources and the thermal control devices is crucial, otherwise the thermal simulation would produce results that vary heavily from previously done hand calculations. For each source of heat the specific part will be selected and the parameter “Heat Generation Rate” will be chosen and set to the desired wattage. Shown in Image 4.15, the microcontroller is set to a power generation rate of 5 watts, which is how much power it is estimated to consume as shown in Table 2.2 and is consistent with the assumptions for the hot case thermal simulations highlighted in section 5.2.3.2.
Moving on to the thermal control devices, these are the core of the simulations and determine how accurate the results are for each configuration. For all thermoelectric coolers, the desired component is selected in the first box, with a “hot face” selected in the next, as shown in Image 4.16 (left). The “hot face” is determined by what side of the thermoelectric cooler will be dissipating heat, since the opposite side is actively cooling the surroundings or the material it is mounted to. Then, the amperage of the cooler is selected, the importance of which is explained in section 3.2.2. For the utilization of heat pipes in the thermal simulations, SolidWorks provides a heat pipe option that allows for any configuration and a combination of any material and working fluid. As outlined in section 3.2.6, the ideal heat pipe for this project has an aluminum casing with a working fluid of ammonia. First, the desired part is selected as the entire heat pipe component, then the hot and cold faces are selected. These faces represent where the pipes are drawing heat from, and where they deposit the heat for the hot and cold sides, respectively. Finally, effective thermal resistance is selected for the specific selection of heat pipes. Effective thermal resistance is a combination of the casing material and working fluid thermal resistances working in conjunction with both the length of the pipes and the total surface area that heat is being pulled from and
deposited to. As expected, this variable can easily be changed to incorporate different combinations of working fluid and casing material.

Image 4.17: Simulation Input Data Part 4

With the project set up, and the input data determined, the last step is to select the project goals. Providing specific goals for the project allows it to effectively converge onto multiple selected parameters to ensure complete and meaningful analysis. Meaningful parameters for this project are temperature values determined from the SatTherm code, power consumptions from the final design configuration, and the average total temperature of the computational domain, which is the only goal desired for simulations.

In order to simulate the atmospheric environment that the CubeSat will be experiencing during orbit, an empirical atmospheric model was utilized to produce details about the composition of the atmosphere at specific geodetic altitudes and coordinates, and based on the year, date, and time of day. This model was produced by the U.S. Navy Research Laboratory (NRL) using a Mass Spectrometer Incoherent
Scatter radar (MSIS). Utilizing this atmospheric model, the user is prompted to enter “Time Type” which gives the option of “Universal” or “Local,” along with the ability to input the year, month, day, and time of day. Next, the Coordinate type is chosen between “Geographic” or “Geomagnetic,” along with the input of latitude, longitude, and a selection of desired altitude between 0 and 1000 km. Setting the altitude is only important depending on the next parameter, the “Profile Type.” This determines what the program will vary to give a broad range of data given the other parameters are kept constant. From here the user is able to specify a range and step size for the given profile type, along with optional input parameters of average F10.7 solar flux sorted by a daily average and a 3-month average. To avoid specifying these optional parameters, the program automatically applies a value of -1 which forces the program to use values from observational data sets. Lastly, there are model parameters calculated by the MSIS that can be chosen to either plot, display in a table, or download to a text file.

For the purposes of this project, the parameters chosen were a universal time, 06/15/2020 at 12:00 pm, geographic coordinates at 55° latitude and 45° longitude, with height being the profile type starting at 0 km and ending at 1000 km by increments of 50 km. The chosen coordinates for this program were based on the default coordinates set by MSIS since the two orbits had yet to be run in the SatTherm code, so there was no information on what coordinates the two orbits might share. Provided the code had been functional earlier, all thermodynamic data of the atmosphere at altitude would be provided and calculated for each coordinate that the hot and cold case are studied at, giving a total of four coordinates. For the calculated MSIS model parameters, everything was chosen and output as a text file that was imported into Excel. This data contains the parameters previously chosen, along with the calculated number densities of monatomic and diatomic oxygen and nitrogen, helium, argon, and hydrogen. Number densities in this context mean the number of molecules of each element present in a given volume, 1 cm^3 in this case. Total mass density is also given for each altitude in g/cm^3 as well as the neutral temperatures which, for the purpose of the project, are not temperatures that will be utilized. Turning this data into relevant and usable numbers involves figuring out the composition of the local atmosphere.
Doing this, equation 4.6.1 was utilized, where $MD_i$ denotes the percent of the total mass density for molecule “i”, $ND_i$ is the number density in cm$^3$, $MM_i$ is the molar mass in g/mol, $N_A$ is Avogadro’s constant in mol$^{-1}$, and $\rho_{Tot}$ is the total mass density at that altitude in g/cm$^3$. With these percentages, every property of the gaseous mixture can be calculated using the properties of the gases that make up the mixture (i.e., a combination of Oxygen and Nitrogen molar masses). The properties that are important for simulation data include specific heat at constant pressure, $c_p$, the specific heat ratio, $k$ or $\gamma$, molar mass, $MM$, thermal conductivity, $K$, and the dynamic viscosity, $\eta$, for the gas mixture at our desired altitude of 600 km. For simulation purposes, a range of data is needed across multiple temperatures for every parameter besides the molar mass and specific heat ratio, so a temperature range from 100K to 400K by increments of 100K was utilized. In order to accurately calculate the desired parameters for the gas mixture, initial data is needed at each temperature value. This data is taken from SolidWorks’ Engineering Database since the simulations are conducted through the same software. SolidWorks provides all the necessary parameters for each individual element; however, monatomic Oxygen and Nitrogen are not included. Due to this lack of information on monatomic properties, diatomic values were utilized. This, coupled with the assumptions that all species are ideal gases and that the atmosphere is a homogeneous mixture, does incur error into the thermodynamic properties of the gaseous mixture and as a result, the thermal simulations.

Finally, with the necessary data from the SolidWorks Engineering Database, the thermodynamic properties of the gas mixture at altitude can be calculated with Equation 4.6.2

$$x = \sum^n_i MD_i \ast x_i$$

(4.6.2)
where $x$ and $x_i$ can be $c_p$, $c_v$, $K$, or $\eta$ for the overall mixture and the individual element, respectively. Since the same equation is used to calculate these thermodynamic properties of the mixed gas, a simple specific heat relation can be used to calculate the molar mass of each mixture by following the equation $MM_{\text{mixture}} = \frac{R}{c_p-c_v}$, where $R$ is the universal gas constant with a value of $8.3145 \text{ J mol}^{-1}\text{K}^{-1}$ and the $c_p$ and $c_v$ values are the specific heats at constant pressure and volume of the mixture, respectively. In total, this gives values for all the thermodynamic properties of a specified mixture, at a specific temperature, and at a specific altitude. Combining the values calculated at the different temperatures stated above, SolidWorks can incorporate this gas mixture and simulate the CubeSat in a more accurate environment.

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>$c_p$ [Jg$^{-1}$K$^{-1}$]</th>
<th>$c_v$ [Jg$^{-1}$K$^{-1}$]</th>
<th>k</th>
<th>$MM$ [g$^{-1}$mol]</th>
<th>$K$ [Wm$^{-1}$K$^{-1}$]</th>
<th>$\mu$ [kg$^{-1}$m$^{-1}s$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.45E+00</td>
<td>8.89E-01</td>
<td>1.63597</td>
<td>14.70368</td>
<td>8.77E-03</td>
<td>1.29E-06</td>
</tr>
<tr>
<td>200</td>
<td>1.48E+00</td>
<td>9.09E-01</td>
<td>1.63066</td>
<td>14.49954</td>
<td>1.43E-02</td>
<td>2.10E-06</td>
</tr>
<tr>
<td>300</td>
<td>1.49E+00</td>
<td>9.16E-01</td>
<td>1.62893</td>
<td>14.42886</td>
<td>1.91E-02</td>
<td>2.78E-06</td>
</tr>
<tr>
<td>400</td>
<td>1.51E+00</td>
<td>9.30E-01</td>
<td>1.62906</td>
<td>14.21265</td>
<td>2.34E-02</td>
<td>3.36E-06</td>
</tr>
</tbody>
</table>

Table 4.1: Thermodynamic Properties of the Atmosphere at 600 km Altitude at Varying Temperatures

Since the CubeSat is in very early design, not all the electronics and components that are inside have been determined, leading to the need of material assumptions for certain components. First, the Etalon is assumed to be a casing made of aluminum 6061 due to this material’s prevalence in many aerospace applications, and a lack of specificity in its actual construction. This assumption has been made for the previously stated reasons, but also due to aluminum being a nonmagnetic metal that is lightweight and provides the necessary strength that is required of many of the components inside of this CubeSat. Next, the scan motors are assumed to be made of stainless steel due to the limited information being given, primarily because a specific model or vendor has yet to be chosen. Electric motors typically have steel
incorporated to induce the electromagnetic field needed for proper operation, that, coupled with the desire to provide worst case scenarios, is why the material for the scan motors is assumed to be stainless steel.

Next, the servo drive motors are assumed to be FR-110 based on the vendors data sheet. FR-110 is a combination of polycarbonate and ABS plastics, but the percentage of each inside was not specified and therefore had to be calculated. Given that the plastic is produced by Bayer’s polymer division, the data sheet for FR-110 was found and a specific gravity value was given as 1.19. This value is translated to a density of 1190 kg/m$^3$ or 1.19 g/cm$^3$. This same data sheet gives a coefficient of thermal expansion of $4.3 \cdot 10^{-5} \text{ in/in/F}$. Given densities of polycarbonate at 1.21 g/cm$^3$ and ABS at 1.07 g/cm$^3$, a simple density system of equations can be created to calculate the thermal properties of FR-110 once all units match up.

\[
x_{PC} \cdot 1.21 \frac{g}{\text{cm}^3} + x_{ABS} \cdot 1.07 \frac{g}{\text{cm}^3} = 1.19 \frac{g}{\text{cm}^3}
\]

(4.6.3)

\[
x_{PC} + x_{ABS} = 1
\]

(4.6.4)

The specific percentage of polycarbonate and ABS that was calculated to be inside of FR-110 is 85.7% and 14.3% respectively when using equations (4.6.3) and (4.6.4). As stated, these values were utilized to calculate equivalent thermal and mechanical properties of FR-110 such as the elastic modulus, thermal expansion coefficient, thermal conductivity, and the specific heat. Next, the camera/detector is assumed to be anodized aluminum due to the manufacturers specification for the specific model chosen by Michigan Aerospace. The microcontrollers are specified to be Beagleboard’s product, BeagleBone Black, which have 6 PCB layers. SolidWorks has a variety of materials for PCB’s that range from 4 to 12 layers, but there is unfortunately no 6-layer option and, with the complexity of the construction of PCB’s, it was decided that a new material would not be created, but rather the microcontrollers would be specified as 8-layer PCB’s during the simulations. For the patch heaters, instead of a combination of materials and adding the complexity of different input data needed for simulations, they are assigned Nickel as the material due to the fact that it is commonly utilized in these thermal control devices. Similar to many passive components within the CubeSat, the heatsink that the thermoelectric cooler is attached
to and the radiator itself are both assumed to be aluminum 6061. Finally, the CubeSat chassis, as stated in section 2.1, is constructed of aluminum 6061.

4.6.2. Simulating Heat Sources

A critical component of simulations involves not only the radiation and heat absorbed on the outside of the CubeSat, but also the internal heat generation. For the specified hot cases, it is assumed that all of the power supplied to each electronic is being dissipated as heat. The power consumption parameters utilized were given by Michigan Aerospace above in Table 2.2 as the average power consumption based on the total power consumption and the duty cycle of each electronic. With this average power consumption, the only components that would produce heat are limited to the scan motors, the detector, and the microcontrollers which are set to heat generation values of 1.5W, 3.6W, and 5W each, respectively. With this defined heat generation coupled with the internal layout of the CubeSat, it is clearly shown in Image 5.35 that the majority of heat would be generated in one general region of the CubeSat primarily. During cold cases, however, every instance of heat generation from pre-existing internal components is disregarded, meaning the only heat generated will be from active forms of thermal control placed for the purposes of this project.

5. Configurations

5.1. Preliminary Configurations

Initial configurations of the CubeSat had thermoelectric coolers being placed in various locations around the CubeSat. Locations consisted of, near the microcontroller, near the camera, and near the etalon, were all designed in an early stage, and done so to attempt to cool the camera to the desired goal of 0 °C. The larger thermoelectric cooler, TE-2-(127-127)-1.15, was employed in the early models of just thermoelectric coolers.
5.1.1. Configuration 0.1

Configuration 0.1 consisted of the thermoelectric coolers near the microcontrollers, with a placement above and below the microcontrollers with the goal of cooling the area generating the most heat. Thermoelectric coolers in the design were placed with the hot side of the thermoelectric cooler on the walls of the CubeSat and the cold side was suspended above and below the microcontrollers. While this design effectively cooled the microcontrollers the amount of heat generated on the hot side of the thermoelectric cooler caused the walls of the CubeSat gain excess heat, thus heating up the rest of the CubeSats internal components. The negatives of the configuration greatly outweigh the cooling effects on the microcontrollers as seen in Image 5.1.

![Image 5.1: Thermoelectric Coolers Near the Microcontrollers](image)

5.1.2. Configuration 0.2

The design with the thermoelectric coolers near the camera had the goal of stopping any of the heat that was radiating from the other electrical components from affecting the camera model. The design
similarly was a basic concept design with a large thermoelectric cooler below the camera, not mounted on any device. The negatives once again outweighed the positives, the hot side of the thermoelectric coolers radiated heat out and once outside the sphere of the cooling side, the heat was immense and adversely affected the camera. The thermoelectric coolers that were chosen did not have an effective heat sink and thus the heat was not able to properly dissipate, Image 5.2.

![Image 5.2: Model with Thermoelectric Cooler Near Camera](image)

### 5.1.3. Configuration 0.3

The design with the thermoelectric coolers near the etalon model had the purpose of trying to maintain the temperature gradient that was imposed. The thermoelectric coolers were placed above and below the etalon, similarly to the camera model, and the same large thermoelectric coolers were used. The configuration provided a very large temperature gradient to the etalon model and did not meet the mission requirements of the temperature gradient, along with the temperature gradient failure the thermoelectric coolers were once again producing more heat to the rest of the CubeSat, greatly outweighing the positives of it cooling the etalon Image 5.3.
A design that had a mixture of all these initial concepts was implemented briefly, but caused the CubeSat walls to reach temperatures that were too high for the material. The combination of the initial designs was not a viable option, all the mission objectives had failed. After evaluating the initial design concepts, a new perspective was introduced with a radiator, thus bringing a new set of designs for the thermoelectric coolers.

5.2. Final Configurations

The final configurations had three designs with two sets of radiator mountings as the primary idea that is contributing to the chosen configurations. With the input of Michigan Aerospace CO on the radiator mount behind the detector and the original design of the radiator mount on the top surface of the CubeSat. Both radiator configurations have different designed heat pipes and layout for thermoelectric coolers.
5.2.1. Configuration 1.1

5.2.1.1. Design

For Configuration 1.1 the radiator is cut into the top surface of the CubeSat, with all two false walls with thermal washers, two thermoelectric coolers, thermoelectric cooler mounting devices, and heat pipes.

To ensure manufacturability of the false walls, each model was designed with considerations for sheet metal fabrication. The false wall near the microcontrollers has a height of 85.27 millimeters, a depth of 93 millimeters, and a width of 2 millimeters. This wall is made of aluminum 6061 sheet metal and is bent to provide adequate room for mounting purposes. There are top and bottom flanges that have two and three mounting holes, respectively, with a flange nearest to the side wall of the CubeSat having two mounting holes. Each hole is paired with a thermal washer to ensure the heat absorbed by the false walls does not conduct to the walls of the CubeSat. All the flanges previously described are bent away from the microcontrollers so as not to obstruct any mounting or connections that may be present in the future. This wall is placed 3.5 millimeters away from the second microcontroller, providing ample room for the lenses and mirrors that direct optics into the camera. To provide ample room for heat pipes to connect to the radiator, a section of the wall was cut out nearest to the radiator. The washers, then, are mounted flush to the false wall as well as the respective walls of the CubeSat.

The false wall near the etalon has a height of 85.27 millimeters and a depth of 62.87 millimeters, the width of the false wall near the etalon is 2 millimeters. The false wall is again made of aluminum 6061 sheet metal with bent flanges again for mounting. The top and bottom flanges have three holes with thermal washers for mounting the false wall, the flange that is nearest the servo control motors has five holes with thermal washers for mounting. Another flange near the optics compartment serves the purpose of blocking the radiative heat from the scan motor. The face of the false wall is 12.4 millimeters from the etalon face, the bent flange is then flush with the wall that is parallel to the servo control motors. The flanges for the mounting are bent away from the etalon while the flange meant for blocking the radiation.
from the scan motor is bent towards the etalon. All the washers are flush with the false wall and the walls of the CubeSat that the washer is mounted to.

The radiator is on the top surface of the CubeSat model, with the hole for the radiator to go through being 50 millimeters by 50 millimeters. The hole is placed 64.96 millimeters from the wall behind the camera and 37.78 millimeters from either wall on the left and right of the camera. The external face of the radiator is 65 millimeters by 65 millimeters, with a thickness of 2.5 millimeters. Under the external radiator face is an aluminum honeycomb core designed to radiate the heat that is transferred to the radiator to the external face. The honeycomb core is 40 millimeters by 40 millimeters and a thickness of 9.65 millimeters, to ensure the honeycomb core does not touch the walls of the CubeSat. Beneath the honeycomb core is a sleeve of aluminum sheet metal, to serve as a mounting surface for heat pipes and to serve as a baffle to block radiation from the radiator from going back into the internal compartment of the CubeSat. The radiator is mounted with four holes, one in each corner, with thermal washers on either side of the top surface of the CubeSat.

The first thermoelectric cooler is placed on top of the camera model, the model is designed to have an interchangeable sizing of the thermoelectric cooler, with a definitive size no larger than 25 millimeters by 16 millimeters, with a thickness of 5 millimeters. The thermoelectric cooler’s hot face is flush a mounting device. The mounting device has a depth of 25 millimeters and is 20 millimeters long, with a width of 11.45 millimeters. The device has two holes on the top surface with thermal washers mounted to the holes to ensure the heat transfer from the hot side of the thermoelectric cooler does not transfer to the top surface of the CubeSat. The mount is made of aluminum 6061 sheet metal, that has a “U-shape” bend to the design for heat piping, the thickness of the sheet metal is set at 2 millimeters. The mounting surface is centered with the camera model, with the back face of the mount being 27.51 millimeters from the wall behind the camera.
The second thermoelectric cooler is behind the camera model, the same design of interchangeable sizing of the thermoelectric cooler is implemented, with the sizing restriction of 25 millimeters by 16 millimeters, with a thickness of 5 millimeters. The same mounting device is being used to stay consistent with the previous thermoelectric cooler design. The mount is in the place centered with the rear of the camera.

![Image 5.4: Top (left) and Isometric (right) View of Configuration 1.1](image)

The sizing of the heat pipes had a variety of factors including the size of the mounting surface, clearance for the heat pipes, and the route each pipe would need to take. There are two primary faces that the heat pipes are composed of with the first being the evaporator, where heat is absorbed, and the second being the condenser, where the heat is removed. For this configuration, the evaporator portion attached to the microcontroller wall is 42 mm wide, 30 mm tall, and 5 mm thick. The remaining evaporating portions are attached to the mountings for each thermoelectric cooler located above and behind the camera model. These portions are similar in shape, with an overall width and height of 14.5 mm and 23.5 mm respectively, while also having a thickness of 5 mm. To ensure maximum heat transfer, the condenser portion was designed to extend across the entire length of the radiator while still providing ample room on either side for mounting. This leads to a length of 62 mm, width of 29 mm, and again, a thickness of 5 mm. Given the scale of the CubeSat, the diameter of the pipe was determined to be 3 mm, which is a readily available size that some manufacturers provide. While it is advised that heat pipes do not have a
bend radius larger than three times their outer diameter, this design and placement had to go against recommendations to effectively attach to the radiator. Given the spatial constraints when determining the microcontroller wall placement, the minimum bend radius experienced by any of the piping is 4 mm, compared to the recommended 9 mm based on the outer diameter utilized.

![Image 5.5: Isometric View of Components of Configuration 1.1](image)

5.2.1.2. Simulation Inputs and Results

The flow simulations of Configuration 1.1 were produced before the SatTherm code was effectively producing accurate data, therefore a method of choosing temperature deviations from the atmospheric temperature at 100 kilometers was introduced. The standard condition at the 100 kilometers is a similar pressure to that of the chosen orbit altitude, with a temperature of 196.605203 K, as referenced in section 4.6.1. The computational fluid was set to air for the simulations of Configuration 1.1 because the atmospheric model had not been completed. Sets of deviations of \(-25\, K, 0\, K, +25\, K, +50\, K, +100\, K\), that were added and subtracted from the given temperature of 196.605203 K. Based on initial knowledge
at this stage in the project these deviations were determined to provide a wide enough range to remain within reasonable bounds, but large enough to consider all eventualities.

The inputs in the simulations done for Configuration 1.1 are the same as input parameters in section 4.6.1. Being the volume sources are all set to the same values, both thermoelectric coolers are set to the Marlow SP1507 with the amperage set to 1.1 A, and the heat pipes having the effective thermal resistance set to $0.01 \frac{K}{W}$. The computational fluid is air set to 100 kilometers, with the temperature deviations previously mentioned.

![Image of Configuration 1.1 at 196.605203 K with Deviation of -25 K Cut Plot](image.png)

**Image 5.6: Configuration 1.1 at 196.605203 K with Deviation of -25 K Cut Plot**

The cut plot shows the fluid temperature at 5 centimeters down from the top surface of the CubeSat, done so to gauge the atmospheric temperatures in the CubeSat model. Starting with the lowest simulated ambient temperature of 196.605203 K with deviation of $-25$ K, 171.203605 K. The cut plot, shown in image 5.6, shows the high temperature of the fluid, being 355.74 K, and the low temperature of the fluid, being 179.71 K. The 355.74 K occurs in the mounting device for the thermoelectric cooler behind the camera, and the cold temperature occurs at the farthest corner of the computational domain that is tested.
in the flow simulation. While the coldest temperature that is observed in the CubeSat model is 215.59 K, found using the SolidWorks probe tool, which occurs in the section behind the etalon model.

Image 5.7: Configuration 1.1 at 196.605203 K with Deviation of -25 K Surface Plots of Etalon (left) and Camera (right)

Continuing with the analysis of the 171.203605 K simulation, the surface plots of both the etalon and the camera, shown in Image 5.7, give insight into the two objectives of the thermal control system as a whole. The temperatures recorded for each are a high temperature of the etalon being 217.82 K and the low temperature of the etalon being 217.8 K, that occurs in the front top right corner of the etalon model and the back bottom right corner of the etalon model. The high and low temperatures of the camera being 280.27 K and 280.08 K, respectively. The hot temperature and cold temperatures of the camera occur near the thermoelectric cooler and the front face of the camera, respectively.
The simulation data that is represented in Image 5.8 demonstrates the 0 K deviation model, showing a cut plot. The high temperature that is shown in the cut plot, Image 5.8, is 365.25 K with the low temperature of the fluid being 202.65 K. The high temperature occurs in the hot side of the thermoelectric cooler, while the low temperature occurs in the farthest corner of the computational domain of the simulation model. The coldest temperature of the fluid that is in the CubeSat can be found using the SolidWorks probe tool to be 229.75 K, occurring near the farthest wall behind the etalon model. The relevance of the fluid temperature isn’t as crucial of a parameter as the solid temperature may be, but the fluid temperature can give an understanding which sections of the CubeSat are generating the most heat and can determine if the electronic device is outside of operating temperatures.
Image 5.9: Configuration 1.1 at 196.605203 K with Deviation of 0 K Surface Plots of Etalon (left) and Camera (right)

The simulation data that is shown in Image 5.9 shows the surface plots of both the etalon model and the camera model, the two crucial components. The left section of image 5.9, demonstrates that the etalon, when simulated at 196.605203 K with 0 K deviation, is reaching a high temperature of 231.89 K and a low temperature of the etalon being 231.87 K, which occurs in the front top right of the etalon and in the back bottom right of the etalon, respectively. The right section of the image 5.9, focuses on the camera at 196.605203 K with the high temperature reaching 288.75 K and reaching a low temperature of 288.57 K, these temperatures take place at the rear face of the camera near the thermoelectric cooler and on the front face of the camera, respectively.
Image 5.10: Configuration 1.1 at 196.605203 K with Deviation of +25 K Cut Plot

Showing the simulation with the deviation in temperature of + 25 K, testing temperature of 221.203605 K, the cut plot shows the fluid temperature results, as shown in image 5.10. The high and low temperatures can be found to be 376.82 K and 226.15 K, respectively. The spots in which the hot and cold temperatures take place in the cut plot remain the same as the previous two simulations. The coldest spot within the CubeSat walls, the section behind the etalon, is at a temperature of 246.60 K.
Image 5.11: Configuration 1.1 at 196.605203 K Deviation of +25 K Surface Plots of Etalon (left) and Camera (right)

Image 5.11 shows the simulated data from the 221.203605 K simulation of the surface plots of the etalon and the camera. The high and low temperatures of the etalon reached 267.48 K and 267.45 K, respectively. The place in which these hot and cold temperatures occur stays consistent with the previous simulations. The high and low temperatures of the camera reach 311.42 K and 311.28 K, respectively. The same spots in which the hot and cold temperatures occur on the camera are the same as the previous simulations.
Image 5.12: Configuration 1.1 at 196.605203 K with Deviation of +50 K Cut Plot

The results for the cut plot from the simulation of + 50 K deviation, ambient temperature of 246.203605 K, are shown in Image 5.12. The maximum and minimum of the fluid temperature results in 389.35 K as the maximum and 250.08 K as the minimum with the positions in which those occur remain consistent with previous simulations of Configuration 1.1. The coldest temperature that is reached inside of the CubeSat is 265.53 K, which occurs once again in the section behind the etalon model.
The surface plots of the etalon and the camera models for the simulation at the deviation of +50 K, as shown in Image 5.13, demonstrate the maximum and minimum temperatures reached on the surface of both the etalon and the camera. The hot and cold temperatures on the surface of the etalon model are 267.48 K and 267.45 K, which occur in the front top right and the back bottom right, respectively. The camera model has surface hot and cold temperatures of 311.42 K and 311.26 K, at the rear face and at the front face, respectively.
The cut plot of the deviation of +100 K, as shown in Image 5.14, produces a high and low temperature of 422.11 K and 298.75 K, respectively. With the high temperature occurring within the thermoelectric cooler mount behind the camera, and the low temperature occurring outside of the CubeSat in the farthest corner of the computational domain. The internal low temperature of the CubeSat results in 307.90 K, found with the probe tool in SolidWorks, which occurs in the section behind the etalon.
Image 5.15: Configuration 1.1 at 196.605203 K with Deviation of +100 K Surface Plots of Etalon (left) and Camera (right)

The surface plots of the etalon and the camera in Configuration 1.1, as shown in Image 5.15, illustrate the hottest and coldest temperatures on the surface of either model. With the etalon model the hottest temperature resulting in 309.69 K and the coldest temperature being 309.66 K. These extremes of the temperature gradient occur at the same locations as the previous simulations. The hottest and coldest temperatures on the camera model surface are 342.04 K and 341.90 K. These hot and cold temperatures are present in the same location as the previous simulation also.

Examining the forms of thermal controls implemented in Configuration 1.1, the false walls, the radiator, and the thermoelectric coolers. The surface heat flux, the rate of heat energy transferred through a given surface, is the key parameter when examining the false walls, radiator, and thermoelectric coolers and the mountings.
Image 5.16: Configuration 1.1 Surface Heat Flux of the Etalon Wall at 0 K Deviation

Image 5.17: Configuration 1.1 Surface Heat Flux of the Microcontroller Wall at 0 K Deviation

Image 5.18: Configuration 1.1 Surface Heat Flux of the Radiator at 0 K Deviation
Images 5.16 and 5.17 show the etalon wall and the microcontroller wall surface heat flux during the 0 K deviation simulation. While Image 5.18 shows the radiator surface heat flux at the simulation of 0 K deviation. The simulation of 0 K deviation is shown to assess the effectiveness of the false wall as a thermal control device, as well as the radiator. As illustrated in the images, the etalon wall reaches a surface heat flux value of \(-57.905 \frac{W}{m^2}\), meaning the wall is absorbing heat on the side near the scan motors, and on the opposite side of the wall, it reaches a value of \(4.078 \frac{W}{m^2}\), meaning the wall is slightly radiating heat. The microcontroller wall in Image 5.17 has a minimum heat flux value of \(-508.116 \frac{W}{m^2}\), absorbing the heat that is coming from the microcontrollers, while the maximum heat flux value being \(39.918 \frac{W}{m^2}\) is radiating the heat the wall has absorbed. The radiator has an absorbing heat flux value of \(382.081 \frac{W}{m^2}\) and a radiating heat flux value of \(15.557 \frac{W}{m^2}\), with the absorbing surface being the section within the CubeSat and the radiating section being the external radiator surface. Interpreting these heat flux values; the false walls effectively absorb the heat at a higher rate than the wall dissipates it. The radiators absorbing heat flux is partially due to the heat pipes transferring heat, and partially due to the mounting surface absorbing the heat that is coming from the microcontrollers.

5.2.1.3. Conclusions

Analyzing the simulation data that is presented as a whole of the simulations done on Configuration 1.1, two primary aspects are taken into account, the temperature of the camera and the overall temperature gradient of the etalon. With the goals of these being the camera remaining at or below 0 °C and an overall temperature gradient on the etalon of 0.1 °C.

First looking at the camera, the temperatures of the simulations remained above the goal of 0 °C. With the temperature of the camera surface during the lowest ambient temperature, a testing temperature of \(-101.95\ °C\), resulting in the camera temperature of 7.12 °C. Throughout simulations as the testing temperature increased the camera model surface temperature got further away from the goal temperature.
of 0 °C. The resultant of the simulation data for the camera goal objective did not reach the desired value during any of the simulations.

Observing the etalon model, the temperature at any given simulation has a rather good temperature gradient, with the gradient across the etalon during the 0 K deviation test being 0.02 °C, the temperature gradient across all simulations has to be considered. The gradient from 0 K deviation to +25 K deviation results in a 35.59 °C gain in temperature, which is out of reasonable consideration for the goal of a gradient of 0.1 °C. As the simulations increased in temperature the gradient across the entire field of simulations grew.

With the consideration of the results from Configuration 1.1, there are aspects of the thermal controls that need to be further developed, such as the radiator placement along with the heat pipe design. Configuration 1.1 overall failed to meet any of the objectives but provided valuable knowledge leading into Configuration 1.2.

5.2.2. Configuration 1.2

5.2.2.1. Design

For Configuration 1.2 the radiator is cut into the wall behind the camera, the configuration has two false walls with the thermal washers mounted to each wall, one thermoelectric cooler, one thermoelectric cooler mounting device, and heat pipes.

The false wall placed near the microcontrollers is the same size as the previous configuration, with a height of 85.27 millimeters and a depth of 93 millimeters, the width of the false wall is 2 millimeters. The false wall is still aluminum 6061 sheet metal and is bent in the same manner as the previous configuration to provide room for the mounting surfaces. The top and bottom flange has three holes each with thermal washers placed between the false wall and the walls of the CubeSat. The side flange closest to the side wall of the CubeSat has two holes in it with thermal washers between the false wall flange and the side wall of the CubeSat. This configuration does not have the cut into the top right corner of the
false wall, this is due to a different heat pipe configuration. The position of the false wall is the same as the previous configuration.

The false wall near the etalon is the same as the previous configuration, with a height of 85.27 millimeters, a depth of 62.87 millimeters, and a thickness of 2 millimeters. The material is aluminum 6061 sheet metal, with four flanges. The top and bottom flange have three holes each for mounting, with thermal washers between the flange face and the CubeSat walls. The flange nearest the camera model has five holes for mounting with thermal washers between the flange wall and the CubeSat wall. The fourth flange is for blocking the heat radiation from the scan motors. The position of the false wall is the same as the previous configuration.

The radiator in the configuration is placed behind the camera model, the same design of the radiator is used as the previous configuration, with different sizing. The hole cut into the CubeSat wall is 35 millimeters by 35 millimeters, being centered with the rear face of the camera model. The external radiator face is 50 millimeters by 50 millimeters, with a thickness of 2 millimeters. The honeycomb core is 30 millimeters by 30 millimeters with a thickness of 7.12 millimeters. The same aluminum sheet metal sleeve design is used for the mounting and baffling, and is resized to 62 millimeters high, with a width of 50 millimeters, the sleeve has a depth of 11.5 millimeters and the metal thickness is 2 millimeters. The four corners of both the exterior face and the interior mounting face have holes for mounting with thermal washers on either side.

The thermoelectric cooler is mounted underneath the camera model with the same mounting device. The placement of the thermoelectric cooler 3.4 millimeters back from the front face of the camera is to reduce the heat coming from the front of the camera. The mounting has the same size as the previous configuration, along with the same thermal washer placement.
Since the radiator is located behind the camera, a different route was needed for the heat pipes, which changed the orientation of the microcontroller wall evaporator. With this changed orientation, the width becomes 60 mm while the height is 40 mm, but the thickness stayed at 5 mm. There is one other evaporating surface located underneath the camera that is attached to a mounting bracket for a thermoelectric cooler. This plate is 13 mm wide and 20 mm long, being an ideal fit to the bracket at 5 mm thick. With heat pipes, both surfaces are then attached to a condenser that is located behind the camera, directly in contact with the radiator. Similar to Configuration 1.1, the heat pipes have an outer diameter of 3 mm. As noted previously in section 5.2.1.1, it is advised that heat pipes do not have a bend radius of more than three times the outer diameter. This recommendation was generally followed through the design of these heat pipes, however due to spatial constraints when connecting to the thermoelectric cooler mounting surface, the bending radius had to be lowered to 6 mm, or two times the outer diameter. Due to similar constraints when attaching piping to the radiator, the path that the heat pipes had to take was not uniform since multiple pipes had to fit between a gap that was roughly 13.6 mm wide, which is not feasible for four heat pipes.
5.2.2.2. **Simulation Inputs and Results**

The flow simulations for Configuration 1.2 were similar in set up to the simulations done for Configuration 1.1 in section 5.2.1.2. The same deviations of -25 K, 0 K, +25 K, + 50 K, + 100 K, form the temperature of 196.605203 K. Due to the results of each simulation from Configuration 1.1 being very similar, the deviations of -25 K, 0 K, and +50 K are chosen to represent the simulation data from the entire Configuration 1.2 simulations.

The inputs of the simulations are the same as section 4.6.2, with the primary difference between the setup of Configuration 1.1 being Configuration 1.2 only having one thermoelectric cooler. The heat piping route has changed since Configuration 1.1, but the heat pipes in Configuration 1.2 still have the same effective thermal resistance.
Image 5.21: Configuration 1.2 at 196.605203 K with Deviation of – 25 K Cut Plot

Image 5.22: Configuration 1.2 at 196.605203 K with Deviation of – 25 K Surface Plots of Etalon (left) and Camera (right)
The Images 5.21 and 5.22 show the cut plot and the surface plots from the simulation done at -25 K deviation. The results of which show that the highest temperature and the lowest temperature recorded with in the CubeSat fluid are 287.68 K and 199.73 K, with the hottest temperature occurring between the microcontrollers and the coldest being in the section behind the etalon. Analyzing the surface plot of the etalon the hot and cold temperatures result in 201.09 K and 201.08 K, respectively. The hot and cold locations on the etalon model stay consistent with the simulation data of Configuration 1.1. The extreme temperatures of the camera are 245.90 K and 245.85 K, with the hottest section being the top of the camera and the front face, and the coldest occurring in the rear of the camera.

*Image 5.23: Configuration 1.2 at 196.605203 K with Deviation of 0 K Cut Plot*
Shown in Images 5.23 and 5.24 the temperatures fields for the 0 K deviation simulation are shown by the cut plot and the surface plots. The cut plot of the entire CubeSat shows the minimum temperature recorded is 217.98 K and the maximum is 296.06 K, these temperatures occur at the same locations as the previous simulation. The temperatures for the surface of the etalon are 219.25 K and 219.24 K, with the spots in which these temperatures are present are the same as the -25 K deviation simulation. The high and low temperatures of the camera are 258.20 K and 258.13 K, respectively.
Image 5.25: Configuration 1.2 at 196.605203 K with Deviation of +50 K Cut Plot

Image 5.26: Configuration 1.2 at 196.605203 K with Deviation of +50 K Surface Plots of Etalon (left) and Camera (right)
Images 5.25 and 5.26 show the simulation data for the +50 K deviation test, with the fluid and surface temperatures being the primary focus. The fluid temperature has a maximum of 320.18 K and a minimum of 258.34 K, with these happening between the microcontrollers and behind the etalon, respectively. The temperatures that the etalon reached ranged from 259.49 K to 259.47 K. The camera model reaches temperatures of 288.97 K and 288.91 K.

Image 5.27: Configuration 1.2 Surface Heat Flux of Etalon Wall at 0 K Deviation

Image 5.28: Configuration 1.2 Surface Heat Flux of Microcontroller Wall at 0 K Deviation
Image 5.29: Configuration 1.2 Surface Heat Flux of Radiator at 0 K Deviation

Images 5.27 and 5.28 show the etalon wall and the microcontroller wall surface heat flux during the 0 K deviation simulation. While Image 5.29 shows the radiator surface heat flux at the simulation of 0 K deviation. As illustrated in the images, the etalon wall reaches a surface heat flux value of $-33.896 \frac{W}{m^2}$, meaning the wall is absorbing heat on the side near the scan motors, and on the opposite side of the wall, it reaches a value of $1.548 \frac{W}{m^2}$, meaning the wall is slightly radiating heat, the same premise as the previous configuration. The microcontroller wall in image 5.27 results in a minimum surface heat flux value of $-283.778 \frac{W}{m^2}$, which is absorbing the heat that is coming from the microcontrollers, while the maximum value being $1.658 \frac{W}{m^2}$, that is radiating the heat the wall has absorbed. The radiator has an absorbing heat flux value of $339.401 \frac{W}{m^2}$ and a radiating heat flux value of $12.516 \frac{W}{m^2}$, with the absorbing surface being the section within the CubeSat and the radiating section being the external radiator surface.
5.2.2.3. Conclusions
Configuration 1.2 was a design that resulted from the objective failure in Configuration 1.1, with the camera model in Configuration 1.1 never reaching below 0 °C and the etalon never remaining within the temperature gradient. The goal of Configuration 1.2 was to achieve one of these goals, to then focus in the next configuration on the one remaining goal.

The camera model remained within the objective for a majority of the simulations, although once the deviations reached above +50 K the camera began to breach the 0 °C goal. The movement of the radiator behind the camera allowed for the heat that the camera generates to dissipate into the radiator, which provided the camera a lower temperature during the simulations compared to Configuration 1.1.

The etalon goal was still not reached due to the temperatures across the multitude of simulations producing a higher temperature gradient than 0.1 °C. The process of maintaining the temperature of the etalon model across all simulations is taken on in the next configuration.

Considering the results of Configuration 1.2 compared to the results of Configuration 1.1 the radiator placement change was adequate but left more to be desired for the higher testing temperatures. Another false wall, placed near the camera model, along with slight modifications to the radiator will be necessary to continue the trend of the camera model remaining within the goal temperature. The etalon model temperature gradient was not satisfactory with the goal, the implementation of an active form of thermal control is needed to achieve the goal for the etalon.

5.2.3. Configuration 1.3

5.2.3.1. Design
Configuration 1.3 is an iteration of Configuration 1.2, with the radiator being utilized in the same position and two of the false walls in the same position and size as Configuration 1.2. Another false wall is added to the configuration with a different thermoelectric cooler position and mounting.

The false wall near the microcontrollers and the false wall near the etalon is the same positioning and sizing as Configuration 1.2, with the same thermal washer placement as the configuration also. The third
false wall is placed near the front of the camera model, with the purpose of reducing the heat radiation from the microcontrollers and the scan motors from reaching the camera model. The false wall has a height of 85.27 millimeters and a width of 50 millimeters. A flange on the top and the bottom have three holes each for mounting to the CubeSat with thermal washers between the flange face and the wall of CubeSat.

The thermoelectric cooler is designed with a fin heat sink and a mounting plate. The heat sink consists of fins that increase the surface area for the heat to transfer to and allow for the hot side of the thermoelectric cooler to transfer the heat efficiently. The fins are 0.4 millimeters thick with 0.78 millimeters of spacing between each fin. The depth of the fin section of the thermoelectric cooler mounting is 12.5 millimeters, with the length and width of the fin section being 34.8 millimeters and 34.55 millimeters respectively. The mounting surface for the thermoelectric cooler is a plate that is the same length and width as the fin section with a depth of 1.25 millimeters. A cut out in the middle of the mounting plate is sized for a thermoelectric cooler to fit and has a usable mounting face of 16 millimeters by 16 millimeters. The thermoelectric cooler can vary in size with a maximum allowable size of 16 millimeters by 16 millimeters with a maximum height of 1.8 millimeters. The placement of the thermoelectric cooler and the mounting device is in the radiator model to ensure the heat that is transferred to the fins can transfer to the radiator effectively. The cold face of the thermoelectric cooler will be in contact with the rear face of the camera model to provide the maximum cooling effect.

The radiator is the same as Configuration 1.2, with the same hole in the CubeSat wall as the previous configuration. The difference between Configuration 1.3 and Configuration 1.2 for the radiator is the aluminum sheet metal sleeve on the interior of the CubeSat. The sleeve has a hole cut into it to provide the fins from the thermoelectric cooler room to get contact with the transfer surface of the radiator model and get the heat from the fins as close to the honeycomb core, without the use of heat pipes.
Previous configurations have focused primarily on the thermal control devices that impact the camera since that is ideally the coldest section of the CubeSat. Now the etalon is taken into consideration by configuring patch heaters on the outer surface, and investigating the wattages needed to accomplish the required temperature gradient of 0.1 °C across the entire component. Patch heaters were uniformly placed around the etalon with a size of 31x25 mm in sets of 3, as illustrated in Image 5.29. These positions were chosen specifically due to the etalon model, we originally obtained having slots and holes along most of the outer surface area, forcing these heaters to be oriented and placed strictly at these locations.

Image 5.30: Patch Heater Placement on Etalon

Image 5.31: Top (left) and Isometric (right) of Configuration 1.3
5.2.3.2. Simulation Inputs and Results

Utilizing the SatTherm temperatures for the hot and cold case obtained from the low inclination orbit, it is concluded that the etalon only needs active heating to reach the desired temperature of 25 °C and a temperature gradient of 0.1 °C. With patch heater placement outlined in section 5.2.3.1, and with the desire for uniform heating all around the etalon, it was decided that a specific ratio would be needed to determine how to distribute the required wattage. This required setting one set of patch heaters as a control and adjusting the other sets to obtain the same temperature values across all three. Set 3 was chosen as the control since it is surrounded by the most “extra” material, meaning the side flanges, and was therefore concluded that it would require the most amount of power to provide similar heat distribution compared to the other sets. The results of this analysis are outlined in Table 5.1 below for both hot and cold case temperatures. In conjunction with these ratios, the calculations for appropriate wattage values for each set of patch heaters can be determined based on Equation 5.1.

\[ Q = mc \frac{dT}{dt} = \frac{mc \Delta T}{t} \]  

(5.1)
Starting with an initial time value of 1.5 hours, the length of one sun synchronous orbit, $\Delta T = 298.15 - T_i$ where $T_i$ is the temperature of the hot or cold case, depending on the simulation, and $Q$ being the required heat transfer rate, an iterative process was developed to accurately converge on correct wattage values. When assumed as aluminum, the mass of the etalon was found to be 0.29 lbm through SolidWorks’ “Mass Properties” tab. For the specific heat of aluminum, the value of $c_p$ is widely accepted to be $0.21 \text{ BTU/lbm}^\circ\text{F}$, leading to the determination of all variables necessary to calculate a wattage. Making this an iterative process, once a simulation had run with the necessary wattage split between the 3 sets of patch heaters, the maximum temperature was utilized to calculate how much “time” SolidWorks took to perform that simulation through Equation 5.2.

$$t_i = \frac{mc\Delta T_i}{Q_i} \quad (5.2)$$

This new time value is then placed back into Equation 5.1 with $\Delta T_i = 298.15 - T_{i-1}$ where $T_{i-1}$ is the maximum temperature of the previous iteration. Tabulated results of the iterative process for both hot and cold cases are shown below in Tables 5.2 and 5.3.
Image 5.32: Surface Plot of Etalon with Final Wattage Ratio

<table>
<thead>
<tr>
<th>Wattage Ratios Needed</th>
<th>Cold Case (K)</th>
<th>213.633</th>
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<tr>
<td>Wattage Values by Set (W)</td>
<td>Set 1</td>
<td>Set 2</td>
</tr>
<tr>
<td>Hot Case (K)</td>
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<td></td>
</tr>
<tr>
<td>Wattage Values by Set (W)</td>
<td>Set 1</td>
<td>Set 2</td>
</tr>
</tbody>
</table>

<table>
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<th>Set 3</th>
</tr>
</thead>
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<td>0.85</td>
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<tr>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
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<tr>
<td>0.85</td>
<td>0.875</td>
<td>0.885</td>
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<tr>
<td>0.8</td>
<td>0.885</td>
<td>0.8875</td>
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Table 5.1: Wattage Ratio Determination for Hot and Cold Cases
<table>
<thead>
<tr>
<th>Last Iteration Temp. (K)</th>
<th>Time For Simulation (h)</th>
<th>Needed Wattage (W)</th>
<th>Hot Case (K)</th>
<th>222.786</th>
<th>Wattage Values by Set</th>
<th></th>
</tr>
</thead>
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<tr>
<td>-</td>
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<td>0.4805</td>
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<td>275.1177</td>
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<td>0.8934</td>
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<td>1.1168</td>
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<td>297.3060</td>
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<td>297.8208</td>
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<td>0.9075</td>
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<td>298.0030</td>
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Table 5.2: Hot Case Wattage Values

<table>
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<th>Last Iteration Temp. (K)</th>
<th>Time For Simulation (h)</th>
<th>Needed Wattage (W)</th>
<th>Cold Case (K)</th>
<th>196.495</th>
<th>Wattage Values by Set</th>
<th></th>
</tr>
</thead>
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<tr>
<td>-</td>
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<td>0.5394</td>
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<td>1.4007</td>
<td>1.5496</td>
<td>1.7509</td>
<td></td>
</tr>
<tr>
<td>298.3080</td>
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<td>4.6924</td>
<td>1.3981</td>
<td>1.5467</td>
<td>1.7476</td>
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</tr>
<tr>
<td>298.1872</td>
<td>0.5789</td>
<td>4.6904</td>
<td>1.3975</td>
<td>1.5460</td>
<td>1.7469</td>
<td></td>
</tr>
<tr>
<td>298.1625</td>
<td>0.5790</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Cold Case Wattage Iterations

In reference to section 4.6.2, the cold case inputs disregard any heat generation from preexisting electronic components. With two active forms of thermal control in this configuration, the thermoelectric cooler does not have any power being supplied to it, while the patch heaters are actively heating the etalon. As mentioned in section 4.5.4 the simulated ambient cold case temperature is 196.495 K. The six patch heaters are set to volume sources, with the wattage for set 1 being 1.3975 W, the wattage for set 2 being 1.5460 W, and the wattage for set 3 being 1.7469 W.
The Images 5.33 and 5.34 demonstrate the fluid temperature of the computational fluid and the surface temperatures of the components of interest. The fluid temperatures reach a low of 211.90 K in the furthest corner from the etalon, while the hottest section of the fluid reaches a value of 298.17 K near the patch heaters. The etalon has a surface temperature heat distribution of 298.16 K to 297.68 K, with the hot spots where the patch heaters are and the cold spots between the patch heaters. The temperature
of the camera model stays the same temperature throughout of 212.04 K. Due to the electrical components being deactivated as state previously, the camera does not experience any temperature gradient, and the primary focus of the cold case study is to maintain a temperature on the etalon as close to 298.15 K as possible.

As stated in section 4.6.2, the hot case has all components dissipating all of the power supplied to it as heat, which leads to multiple different sources of heat. With the camera wall preventing much radiative heat from reaching it, the thermoelectric cooler does not have any power being supplied since the camera is already below 0 °C as shown in Image 5.36, accomplishing one of our two goals. Since one goal has been reached, this simulation is mainly focused on maintaining a temperature of 25 °C on the etalon, with a temperature gradient of 0.1 °C or less. This simulation was done at an ambient temperature of 222.786 K, or -50.364 °C, as outlined in section 4.5.4. As shown above in Table 5.2, set 1 of the patch heaters was set to a heat generation rate of 0.9104 W, set 2 was 1.0100 W, and finally, set 3 had a value of 1.1381 W for each patch heater in their respective set.
As illustrated in Image 5.3, the fluid temperature inside the CubeSat comes primarily from the microcontrollers, leading to the coldest portion, a temperature around 247.72 K, being in the opposite corner of the CubeSat, located behind the etalon. The maximum temperature reached in Image 5.3 being 365.28 K located directly inside of the scan motor closest to the outer wall of the CubeSat. The temperature gradient seen in Image 5.3 is due to the nature of the hot case and the heat generation from components other than the patch heaters, leading to a maximum and minimum temperatures of 253.54 K and 252.66 K respectively. For the etalon, the maximum and minimum temperatures are 298.16 K and 297.84 K based on the wattage values determined in Table 5.2.

### 5.2.3.3. Conclusions

Configuration 1.3 brought the goals of the previous configurations to the forefront, with the ambition of achieving the goals. The first goal of keeping the camera at or below 0 °C and the second goal of reaching a temperature gradient of 0.1°C on the etalon.

Starting with the camera model, the temperature of the CubeSat as a whole, with thermal paint, does not reach above 0 °C, therefore providing the cold case with already reaching the goal. During the cold case the temperature of the camera does not provide a point of interest due to the nature of the cold case being the camera is deactivated. The hot case with all the electronics activated the camera still does not
reach 0 °C, getting to -19.65 °C at the hottest. The hot case temperature of the camera provides enough
evidence that throughout the orbits chosen the camera will remain below 0 °C. The thermal paint
provided low enough temperatures to avoid the deployment of the thermoelectric cooler, while the false
wall in front of the camera blocked the heat that escaped around the false wall in front of the
microcontrollers.

Analyzing the hot and cold cases, the temperature gradient for each simulation is 0.33 °C and 0.48
°C, respectively. The difference between the maximum and minimum temperatures for both cases is 0.01
°C and 0.16 °C, respectively. While the gradient across the etalon is worse compared to previous
configurations, a form of active thermal control was necessary in maintaining an average temperature of
25 °C across the range of ambient temperatures.

5.3. Cost Analysis

Although cost was not a primary concern during the development of the thermal control system, an
estimate cost of the materials to create the system is still useful to have. The following table can also
serve as a bill of materials for this system. The cost analysis table is broken down into the following
parts: amount required, unit size, cost per unit, cost – with excess, and cost – no excess. The amount
required is the exact amount of material that needs to be consumed to create one instance of the thermal
control system. The unit size is the smallest amount of material that could be ordered at a time through a
given online vendor. The cost per unit describes the cost of that amount of material. The cost – with
excess column describes the total cost of one thermal control system if enough material was purchased
using the smallest unit sizes offered by the online vendors. It should be noted that due to the relatively
small amount of material needed for the thermal control system an excess amount of material will remain
after the construction of a single thermal control system. The cost – no excess column considers the cost
if the exact amount of material needed could be purchased with no excess. A quote was requested from
AZ Technology concerning the cost of their AZ-93 thermal paint, but a response was not received in time to include the estimate in the bill of materials.

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount Req.</th>
<th>Unit Size</th>
<th>Cost per Unit</th>
<th>Cost – With Excess</th>
<th>Cost – No Excess</th>
</tr>
</thead>
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<td><strong>Aluminum Honeycomb Panel</strong></td>
<td>2.48 in²</td>
<td>12” x 12” Sheet</td>
<td>$69.70</td>
<td>$69.70</td>
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<td><strong>Aluminum Heatsink</strong></td>
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<td>40mm x 40mm x 20mm – Pack of 4</td>
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<td>$9.99</td>
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<td><strong>Aluminum 6061 Sheet – 0.05”</strong></td>
<td>1.88 in²</td>
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<td>$17.83</td>
<td>$0.23</td>
</tr>
<tr>
<td><strong>Aluminum 6061 Sheet – 0.08”</strong></td>
<td>52.25 in²</td>
<td>12” x 12” Sheet</td>
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<td>$23.53</td>
<td>$8.54</td>
</tr>
<tr>
<td><strong>Aluminum 6061 Sheet – 0.1”</strong></td>
<td>3.87 in²</td>
<td>12” x 12” Sheet</td>
<td>$37.75</td>
<td>$37.75</td>
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<tr>
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<td>1” x 1” Sheet</td>
<td>$82.55</td>
<td>$495.30</td>
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<tr>
<td><strong>PEEK Washer</strong></td>
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<td>Pack of 10</td>
<td>$4.39</td>
<td>$17.56</td>
<td>$13.61</td>
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<tr>
<td><strong>TEC (Marlow SP1507)</strong></td>
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<td>1 TEC</td>
<td>$50.96</td>
<td>$50.96</td>
<td>$50.96</td>
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<tr>
<td><strong>Total cost</strong></td>
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<td></td>
<td>$722.62</td>
<td>$573.35</td>
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</tr>
</tbody>
</table>

*Table 5.4: Cost Breakdown of Thermal Control System*
5.4. Mass Analysis

The mass of any payload being sent into orbit is one of the most important parameters of any spacecraft mission. For a 6U CubeSat, the maximum mass should not exceed 12kg. In Table 5.5 it is observed that the majority of the mass of the thermal system comes from the false walls and TEC mounting due to the high amount of sheet metal being used in these components.

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch Heater</td>
<td>2.88 (x6)</td>
</tr>
<tr>
<td>PEEK Washer</td>
<td>0.15 (x31)</td>
</tr>
<tr>
<td>False Walls</td>
<td>188.55</td>
</tr>
<tr>
<td>Honeycomb Panels</td>
<td>51.02</td>
</tr>
<tr>
<td>TEC</td>
<td>2.81</td>
</tr>
<tr>
<td>TEC Mounting</td>
<td>190.82</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>455.13</strong></td>
</tr>
</tbody>
</table>

*Table 5.5: Weight Breakdown of Thermal Control System*
6. Conclusion

The objective of this project was to create a thermal control system for use in a 6U CubeSat. The project goals given by Michigan Aerospace stated that the etalon inside the satellite must remain at a low thermal gradient of 0.1 °C, and the detector must remain at a temperature below 0 °C. In the end, the team was able to partially meet these requirements by finding a thermal control configuration that kept the detector to its recommended temperature, but some difficulty arose in trying to meet the temperature requirements of the etalon. The best temperature gradient across the etalon that was able to be achieved at the end of the project timeline was 0.33-0.48 °C.

Finding an adequate internal configuration proved to be a difficult challenge to effectively meet the requirements set by Michigan Aerospace. Through multiple configurations and hundreds of hours of simulations, a final internal design was created to conform to the temperature limit for the detector, but ultimately failed to meet the strict temperature gradient required for the etalon. For the hot and cold case simulations, the detector had consistently been kept well below 0 °C, and since the ambient temperatures were around 80-100 °C colder than what the etalon needed, a gradient of 0.33-0.48 °C was achieved. While this is larger than what was initially desired, it had been deemed acceptable given the limitations and obstacles faced throughout the project.

The thermal analysis done by the SatTherm program proved to produce results that were both consistent and realistic. SatTherm proved especially useful in providing quick results for simulations with different input parameters such as different orbits or different types of thermal paints. Finding a working instance of the SatTherm program proved to be difficult during the beginning of the project, but once this program properly functioned it became an important tool.

Overall, CubeSats and other small form factor satellites have become a great resource for small organizations and universities to learn more about satellites and the great information they can offer. The research done in this paper will hopefully provide some insight to how the internal thermals of a CubeSat can be effectively managed while minimizing active forms of thermal control.
7. Future Design Recommendations

While the SatTherm code closely resembles Thermal Desktop and the results were highly similar, a margin of error exists between both software. For a more in-depth and accurate assessment, it would be recommended to further analyze the transient temperature of the satellite with software dedicated towards thermal analysis, such as Thermal Desktop, Sinda, or Thermica.

Considering the continuation of the designs in section 5.2, recommendations for future development were a contingency of the project. Considering the results of the simulation data from the Configurations 1.1, 1.2, and 1.3, the best course of action is further development of Configuration 1.3, with a bulk of the development relying on achieving the temperature gradient of 0.1 °C.

Patch heater wattage designs were done through an iterative process with the spacing of the patch heaters being a variable in the process. Ideally, if an iterative process is done for the patch heaters the spacing between each patch heater needs to be equal and remain consistent. Due to the design constraints of the etalon, spacing of the patch heaters in Configuration 1.3 were placed as close to equal as possible. Continuing with the design from Configuration 1.3, a feedback system, such as a PID controller, would likely need to be implemented to adjust the specific wattages of each patch heater independently based on temperature measurements. With this more advanced control over the wattages of the patch heaters a lower temperature gradient would be achieved.

Ambient conditions were not known for the majority of the project, resulting in some forms of thermal control being redundant in the final designs. Considering the recommended change mentioned previously to Configuration 1.3, a different implementation of the radiator is suggested. The radiator was effective at conducting heat that the camera generated, and effectively dissipated the heat into space. Redundancy occurred with the thermoelectric cooler and its heat sink. While the thermoelectric cooler mounted to the radiator would effectively cool an area and provide ample conductance for the heat sink, the ambient temperatures reached would not suffice the added weight of the design. Following with the
recommended process done to control the patch heaters, the recommendation to remove the thermoelectric cooler and the heat sink that supports it would reduce weight and cost, while not jeopardizing the goal of remaining below 0 °C.

Final considerations would also include adding a temperature measurement tool, such as a thermistor or a thermocouple. Multiple of these would likely need to be placed in critical locations inside the CubeSat to ensure the patch heaters are receiving accurate data. With these recommendations the CubeSat thermal control system can be fine-tuned to achieve the goals of the mission more efficiently.
8. References


9. Appendix I - ABET Questionnaires

9.1. ABET Questionnaire 1 – Luke Bartley

Student Name: Luke Bartley

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
3. Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
4. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)

**Performance Indicator 1**

Describe the engineering needs for this project.

Most of the engineering needs required for this project were provided by the school. Engineering needs for this project consisted of different kinds of software to carry out various simulation and analysis tasks. MATLAB was used the external thermal analysis of the satellite while SOLIDWORKS flow simulation was used to determine the internal thermal analysis of the satellite and design the components of the thermal control system.

List the project goals along with performance criteria.

The goal of this project was to meet the requirements set by Michigan Aerospace Corporation. Certain internal components specified by MA had to be maintained at a certain temperature in order to maintain proper functionality. The first component that required thermal control was the etalon, where the requirement set by MA was a thermal gradient of 0.1 Celsius. Our group was able to reach a value of 0.4-0.5 Celsius but it is believed that better results are possible with a more complex simulation method. The second goal was to keep the detector below 0 Celsius, and this was achieved convincingly.

List the project constraints.
The main constraint was that the chassis must be kept at a certain size, so the size and placement of the thermal control system design was a large consideration. A second constraint was the orbit that the satellite had to be tested on. Two possible orbits were defined by MA and each had unique levels of thermal fluctuation.

List the methods/procedures that were implemented to ensure that the customer expectations were addressed.

In order to meet the expectations of MA the testing parameters for the SOLIDWORKS simulations were set to be as close as possible to the real conditions. Theoretical calculations were also done to determine key parameters (hot and cold cases). Weekly meetings with MA were also done to make sure the correct steps were being taken.

**Performance Indicator 2**

Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health:

For this project public health and safety was not a major concern due to the nature of satellites typically being far from the public. Any aspects of the satellite that might be a concern to other satellites such as maneuvering systems or communications systems fall under tasks that would be out of the scope of our project to design a thermal control system.

Public safety:

See Public health.

Public welfare:

See Public health.

**Performance Indicator 3**

List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors:

NA
Cultural factors:
NA

Social factors:
NA

Environmental factors:
NA

Economic factors:
NA

**Performance Indicator 4**
(To be addressed by the faculty adviser).

Outcome (4) An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental and societal contexts.

**Performance Indicator 2:**
Student is able to make informed judgments based on the impact of engineering solutions in global, economic, environmental and societal context.

Did you adapt your project to make it useful in many countries? **Y / N / NA** If yes, explain:

N/A

Did you consider standards and regulations, either U.S. or international? **Y / N / NA** If yes, explain how they affected your project:

N/A
Did you consider the effects of manufacturing in various locations? Y/N/NA If yes, where in the report did you address this issue?

N/A

Did you have to balance effects of costs and performance? Y/N/NA If yes, explain and refer to the report as appropriate.

N/A

Did you consider effects of maintenance, failure and repair on cost, safety, etc.? Y/N/NA If yes, where in the report did you address them?

Yes. These are referenced in sections 5.1.3.

What were your considerations (e.g., cost, weight, manufacturing, availability, safety, recycling, etc.) in the selection of materials? List, explain and refer to the text of the report as appropriate.

Cost Considerations: Section 5.2
Weight Considerations: Section 5.3
Manufacturing Considerations: Section(s) 5.2

Does your project impact air quality, water quality, noise levels, and other environmental aspects? Y/N/NA If yes, explain how and show what were your actions.

N/A

Does your project impact human health during manufacturing or normal use? Y/N/NA If yes, explain what you did to alleviate the risks.

N/A

Are there any other safety issues typical to your project? Y/N/NA If yes, explain your decisions and actions. Refer to the report as appropriate.

No.
Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives

Performance Indicators:

1. Student’s ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks

(If you copy and paste from the report, mention Section number or page numbers.)

Performance Indicators 2 & 5

List all tasks required to accomplish the goals of this project, and name the group member responsible for the completion of each task.

a. Team Lead – Lukas Hayes
   a. Primarily responsible for communication between the industry sponsor, faculty advisor, and team members. Organized meetings and direction for project completion.

b. Research of methods of thermal control – No particular leader; Team deliverable
   a) Luke Bartley: Thermal washers
   b) Lukas Hayes: MLI, thermoelectric coolers (TEC), radiators, thermal washers, false walls
   c) Callie Pilkington: Thermal paint
   d) Justin Poole: Heat pipes, patch heaters, false walls, heat straps

b. Orbital parameter determination – Callie Pilkington

c. Hot and cold case parameters – Callie Pilkington, Justin Poole
   a) Callie Pilkington: Leader for hot and cold case parameters used in SatTherm
   b) Justin Poole: Leader for hot and cold case parameters in SolidWorks

d. SolidWorks CubeSat models – Luke Bartley, Lukas Hayes, Justin Poole
   a) Luke Bartley: Simplified/defeatured CubeSat model
   b) Lukas Hayes: Co-lead for SolidWorks thermal control models and arrangement
   c) Justin Poole: Co-lead for SolidWorks thermal control models and arrangement

e. SolidWorks simulations of CubeSat – Lukas Hayes, Justin Poole
   a) Lukas Hayes: Leader for cold case simulations
   b) Justin Poole: Leader for hot case simulations

f. SatTherm simulations of CubeSat – Luke Bartley, Callie Pilkington
   a) Luke Bartley: Leader for determination of array sizes and fixed errors
   b) Callie Pilkington: Leader for simulations of orbits and hot or cold cases
Performance Indicator 1
(Project’s adviser will determine whether the listed tasks were completed).

Answer the following questions:

For project tasks in which I was not the leader, I provided the following inputs towards their completion:

SOLIDWORKS Simulations:
Suggested that the simulations should be done with simplified model, suggested looking at alternative simulation software (Ansys Icepak) but it was decided to continue with SOLIDWORKS.

SatTherm Simulations:
Assisted in determining proper array sizes for the program, as well as fixing various bugs within the code. Did hand calculations for some of the variables used in the SatTherm program.

Performance Indicator 3
For project tasks in which you were the leader, describe the input other group members provided towards the successful completion of these tasks.

Name of Student 1: Lukas Hayes
In general Lukas was able to provide support as a project leader by helping to keep the project moving forward at a sufficient pace. He was also able to provide some models for the defeatured CubeSat.

Name of Student 2: Callie Pilkington
Callie provided assistance in fixing any bugs in the SatTherm program. Callie was also able to determine the final value of emissivity and absorptivity used for the SatTherm simulations of the satellite. She was also able to contribute a lot to the heat transfer simulations in both the SatTherm program and hand calculations.

Name of Student 3: Justin Poole
Justin was able to help provide hot and cold cases for the SatTherm simulations. He was also able to provide some models for the defeatured CubeSat.

Performance Indicator 4
List all goals this project had to satisfy to be considered successfully completed.

The goal of this project was to meet the requirements set by Michigan Aerospace Corporation. Certain internal components specified by MA had to be maintained at a certain temperature in order to
maintain proper functionality. The first component that required thermal control was the etalon, where the requirement set by MA was a thermal gradient of 0.1 Celsius. Our group was able to reach a value of 0.4-0.5 Celsius but it is believed that better results are possible with a more complex simulation method. The second goal was to keep the detector below 0 Celsius, and this was achieved convincingly.

**Performance Indicator 6**
(To be addressed by the faculty adviser).

**Outcome (7)** An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

1. Student’s ability to find information relevant to problem solution without guidance.
2. Student’s ability to identify the additional knowledge needed to complete project.
3. Student’s ability to acquire and apply the additional knowledge needed to complete project.

**Performance Indicator 1**

Describe what information you found in order to successfully complete the tasks you were assigned in the project.

Before this project not many details about CubeSats were known personally, but each member of the group had a working understanding of orbital mechanics from previous classes. In order to complete the theoretical calculation of the hot and cold cases some information found from reports regarding solar flux was utilized. For tasks regarding the use of software, online tutorial videos were useful.

What sources did you use to find this information?

Over the course of this project numerous sources on the topic of CubeSats were accessed. These sources included previous senior design reports, scientific journal articles, and informational PowerPoints from reputable educational sources. For information about performing simulations, online tutorial videos were utilized.

**Performance Indicator 2**
Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

For this project my tasks required additional knowledge of orbital mechanics, heat transfer, and a little bit of CAD modeling. Much of the heat transfer equations used to calculate the solar flux and other flux were unknown to me previously, so that is all completely new information that I had to learn. Knowing the thermal properties of various materials was also important during this project.

**Performance Indicator 3**

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

In order to improve the additional skills needed for this project I spent some time reviewing previous instances of MATLAB code that I have created, as well as looking at videos online to help regarding SOLIDWORKS tasks.
9.2. ABET Questionnaire 2 – Lukas Hayes

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:
1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
3. Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
4. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)

Performance Indicator 1
Describe the engineering needs for this project.

The needs of the project were SolidWorks, MATLAB, knowledge of heat transfer, orbital mechanics, and thermodynamics. These needs enabled us to understand the SolidWorks flow simulations and the NASA SatTherm Code.

List the project goals along with performance criteria.

The goals of the project are presented in section 1.2 project objectives. Along with the goals from Michigan Aerospace the performance criteria are a result of the simulation data from the temperatures of the etalon and detector.

List the project constraints.

The constraints for the design are in section 1.3 design constraints. Also involved in the constraints are the limitations of software availability and altitude parameter constraints in SolidWorks.

List the methods/procedures that were implemented to ensure that the customer expectations were addressed.

The customer expectations are presented in section 1.2 in project objectives

Performance Indicator 2
Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health:
N/A

Public safety:
N/A

Public welfare:
N/A

**Performance Indicator 3**
List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors:
N/A

Cultural factors:
N/A

Social factors:
N/A

Environmental factors:
N/A

Economic factors:
N/A

**Performance Indicator 4**
(To be addressed by the faculty adviser).

Outcome (4) An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental and societal contexts.

**Performance Indicator 2:**
Student is able to make informed judgments based on the impact of engineering solutions in global, economic, environmental and societal context.

Did you adapt your project to make it useful in many countries? Y / N / NA If yes, explain:

N/A

Did you consider standards and regulations, either U.S. or international? Y / N / NA If yes, explain how they affected your project:

N/A

Did you consider the effects of manufacturing in various locations? Y / N / NA If yes, where in the report did you address this issue?

N/A

Did you have to balance effects of costs and performance? Y / N / NA If yes, explain and refer to the report as appropriate.

N/A

Did you consider effects of maintenance, failure and repair on cost, safety, etc.? Y / N / NA If yes, where in the report did you address them?

Yes, in section 5.1.3 for configuration 1.3 the design had redundancy with the thermoelectric cooler implementation.

What were your considerations (e.g., cost, weight, manufacturing, availability, safety, recycling, etc.) in the selection of materials? List, explain and refer to the text of the report as appropriate.

In section 5.2 the cost analysis and in section 5.3 weight analysis.

Does your project impact air quality, water quality, noise levels, and other environmental aspects? Y / N / NA If yes, explain how and show what were your actions.

N/A

Does your project impact human health during manufacturing or normal use? Y / N / NA If yes, explain what you did to alleviate the risks.

N/A

Are there any other safety issues typical to your project? Y / N / NA If yes, explain your decisions and actions. Refer to the report as appropriate.

N/A
Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives

Performance Indicators:

1. Student’s ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks

(If you copy and paste from the report, mention Section number or page numbers.)

Performance Indicators 2 & 5
List all tasks required to accomplish the goals of this project, and name the group member responsible for the completion of each task.

a. Project Manager – Lukas Hayes
b. Research of methods of thermal control – No particular leader; Team deliverable
   i. Luke Bartley: Thermal washers
   ii. Lukas Hayes: MLI, thermoelectric coolers, radiators, thermal washer, false walls
   iii. Callie Pilkington: Thermal paint
   iv. Justin Poole: Heat pipes, patch heaters, false walls, heat straps
b. Orbital parameter determination – Callie Pilkington
c. Hot and cold case parameters – Callie Pilkington, Justin Poole
   i. Callie Pilkington: Leader for hot and cold case parameters used in SatTherm
   ii. Justin Poole: Leader for hot and cold case parameters in SolidWorks
d. SolidWorks CubeSat models – Luke Bartley, Lukas Hayes, Justin Poole
   i. Luke Bartley: Simplified CubeSat chassis
   ii. Lukas Hayes: Co-lead of all designed layouts of all configurations
   iii. Justin Poole: Co-lead of all designed layouts of all configurations
e. SolidWorks simulations of CubeSat – Lukas Hayes, Justin Poole
   i. Lukas Hayes: Co-lead for camera goal and cold case for the etalon goal
   ii. Justin Poole: Co-lead on camera goal and hot case for etalon goal
f. SatTherm simulations of CubeSat – Luke Bartley, Callie Pilkington
   i. Luke Bartley: Determination of array sizes and fixed errors
   ii. Callie Pilkington: Leader for simulations of orbits and hot or cold cases

Performance Indicator 1
(Project’s adviser will determine whether the listed tasks were completed).

Answer the following questions:

For project tasks in which I was not the leader, I provided the following inputs towards their completion:
SatTherm code: Communicated to my team members that worked on the SatTherm portion the importance of maintaining productivity levels and ensuring tasks are completed within the designated timeframe. I emphasized the need for proactive effort and continuous improvement and encouraged everyone to take ownership of their responsibilities.

Hot case Simulations: Determined iteration methods with Justin for the patch heater wattage.

Hot and Cold case parameters: Advised in using both orbits and taking the extremes of each for the determination of hot and cold case.

SatTherm documentation: Assisted Justin in the initial documentation of the code, in which we wrote the code, fixing syntax errors and created an input page. Advised on design characteristics of external thermal controls implemented in the code.

**Performance Indicator 3**
For project tasks in which you were the leader, describe the input other group members provided towards the successful completion of these tasks.

Name of Student 1: Luke Bartley

Provided defeatured CubeSat model that lessened simulation run time.

Name of Student 2: Callie Pilkington

Provided simulation data from the SatTherm code for both orbits and for extremes of hot and cold cases.

Name of Student 3: Justin Poole

Justin was a great asset to the team in many respects, he took half of the SolidWorks load, he alleviated a lot of the stresses for me as the elected team lead, he spent the most hours out of anyone on the team on the project. For the thermoelectric cooler simulations Justin provided valuable insight into transferring heat in form of heat pipes. Cold case simulations of the etalon, Justin made the initial parameters before the iteration method was implemented. Justin made the job of team lead very easy for the SolidWorks side of the project due to him being very resourceful and motivated to work.

**Performance Indicator 4**
List all goals this project had to satisfy to be considered successfully completed.

Maintained temperature of 0 °C for the camera. Maintained the temperature gradient of 0.1 °C for the etalon.

**Performance Indicator 6**
(To be addressed by the faculty adviser).
Outcome (7) An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

1. Student’s ability to find information relevant to problem solution without guidance.
2. Student’s ability to identify the additional knowledge needed to complete project.
3. Student’s ability to acquire and apply the additional knowledge needed to complete project.

Performance Indicator 1

Describe what information you found in order to successfully complete the tasks you were assigned in the project.

Researched flow simulations using multiple forums, such as the initial setup in the Flow Simulation Wizard and the use of multiple forms of heat sources in the simulations. Researched about many thermoelectric coolers and heat sink options, in order to maintain the camera goal.

What sources did you use to find this information?

SolidWorks official website, manufacturers website of thermoelectric coolers.

Performance Indicator 2

Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

People management, SolidWorks knowledge, orbital parameters, heat transfer knowledge, material properties knowledge.

Performance Indicator 3

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

For knowledge about specific topics such as orbital parameters, heat transfer, and material properties textbooks and previous class notes were used. For the SolidWorks knowledge, a base knowledge of how to use the software was acquired by trial and error with the software, the more advanced knowledge with the thermal aspect of SolidWorks was acquired from the official website and instructional videos. People management skills were already present, but were refined during the duration of the project through perseverance.
9.3. ABET Questionnaire 3 – Callie Pilkington

Student Name: Callie Pilkington

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
   • Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
3. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)

Performance Indicator 1
Describe the engineering needs for this project.

- Software to simulate internal thermal changes of the thermal control methods.
  - Fulfilled by SolidWorks
- Software to simulate transient temperature fluctuations of the satellite in orbit.
  - Fulfilled by SatTherm via MATLAB.
- Knowledge of heat transfer and thermodynamics.
- Knowledge of Keplerian orbits.

List the project goals along with performance criteria.

- Provide a suitable method of thermal control for a CubeSat that maintains two separate temperatures (See Section 1.2).
  - Maintain camera/detector temperature at or below 0 °C.
  - Limit etalon/interferometer temperature to 25 °C with a temperature gradient of 0.1.

List the project constraints.

- Power, volume, and weight constraints related to the CubeSat (See Section 3.2).
- Orientation, altitude, and orbit specifications (See Section 1.3).
- Software and license limitations (See Section 4.2).

List the methods/procedures that were implemented to ensure that the customer expectations were addressed.
• Regular communication with the industry sponsor to receive clarification or advice.
• Testing parameters for SatTherm and SolidWorks simulations were tailored to the customer’s requirements (See Sections 1.2, 1.3).
• Hot and cold case parameters were chosen to make conservative estimates and prepare for extreme scenarios (See Section 4.1.3).

**Performance Indicator 2**
Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health:

With the CubeSat in far proximity from any civilians, public health and safety were not a primary concern. Satellites can be a danger to other orbiting satellites; however, this is a concern that should be more carefully reviewed when determining the final orbit and launch location of the CubeSat.

Public safety:

N/A

Public welfare:

N/A

**Performance Indicator 3**
List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors:

Satellites will be used in international space. There is the possibility of multiple satellites being used in a constellation, which could impact other satellites already in orbit.

Cultural factors:

N/A

Social factors:

N/A

Environmental factors:
There is no international requirement for satellites to be deorbited or removed. Satellites left up in orbit past their operational date can clog up the Low Earth Orbit (LEO) range and can hit other satellites. Debris build up could render LEO range unusable.

Economic factors:

N/A

**Performance Indicator 4**
(To be addressed by the faculty advisor).

Outcome (4) An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental and societal contexts.

**Performance Indicator 2:**
Student is able to make informed judgments based on the impact of engineering solutions in global, economic, environmental and societal context.

Did you adapt your project to make it useful in many countries? Y / N / NA If yes, explain:

N/A – This project should not have any issues related to use by different countries.

Did you consider standards and regulations, either U.S. or international? Y / N / NA If yes, explain how they affected your project:

N/A – Industry sponsor did not specify standards or regulations to follow.

Did you consider the effects of manufacturing in various locations? Y / N / NA If yes, where in the report did you address this issue?

N/A – The manufacturing locations of the various thermal control methods was not extensively reviewed, although there should be no issue.

Did you have to balance effects of costs and performance? Y / N / NA If yes, explain and refer to the report as appropriate.

N/A – Cost estimates for the thermal control methods were made, however there was little analysis comparing cost and performance, as we were not given a particular budget or cost cap.

Did you consider effects of maintenance, failure and repair on cost, safety, etc.? Y / N / NA If yes, where in the report did you address them?

Y – Redundancy is implemented in Configuration 1.3 with thermoelectric coolers (See Section 5.1.3).
What were your considerations (e.g., cost, weight, manufacturing, availability, safety, recycling, etc.) in the selection of materials? List, explain and refer to the text of the report as appropriate.

Cost, weight, and manufacturing considerations are expanded upon in Section 5. (See Section 5.2, 5.3).

Does your project impact air quality, water quality, noise levels, and other environmental aspects? Y / N / NA If yes, explain how and show what were your actions.

N – The only environmental aspects that could be considered relate to space debris, which is referenced above.

Does your project impact human health during manufacturing or normal use? Y / N / NA If yes, explain what you did to alleviate the risks.

N – There are no expected health risks during manufacturing or normal use.

Are there any other safety issues typical to your project? Y / N / NA If yes, explain your decisions and actions. Refer to the report as appropriate.

N – There are no directly related safety issues concerning the project. Space debris risks are referenced above, although this risk extends beyond the scope of the project’s involvement.

Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives

Performance Indicators:

1. Student’s ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks

(If you copy and paste from the report, mention Section number or page numbers.)

Performance Indicators 2 & 5
List all tasks required to accomplish the goals of this project, and name the group member responsible for the completion of each task.

c. Team Lead – Lukas Hayes
   a. Primarily responsible for communication between the industry sponsor, faculty advisor, and team members. Organized meetings and direction for project completion.

d. Research of methods of thermal control – No particular leader; Team deliverable
e) Luke Bartley: Thermal washers
f) Lukas Hayes: MLI, thermoelectric coolers (TEC), radiators, thermal washers, false walls
g) Callie Pilkington: Thermal paint
h) Justin Poole: Heat pipes, patch heaters, false walls, heat straps
c) Orbital parameter determination – Callie Pilkington
d) Hot and cold case parameters – Callie Pilkington, Justin Poole
c) Callie Pilkington: Leader for hot and cold case parameters used in SatTherm
d) Justin Poole: Leader for hot and cold case parameters in SolidWorks
e) SolidWorks CubeSat models – Luke Bartley, Lukas Hayes, Justin Poole
d) Luke Bartley: Simplified/defeatured CubeSat model
e) Lukas Hayes: Co-lead for SolidWorks thermal control models and arrangement
f) Justin Poole: Co-lead for SolidWorks thermal control models and arrangement
f) SolidWorks simulations of CubeSat – Lukas Hayes, Justin Poole
c) Lukas Hayes: Leader for cold case simulations
d) Justin Poole: Leader for hot case simulations
g) SatTherm simulations of CubeSat – Luke Bartley, Callie Pilkington
c) Luke Bartley: Leader for determination of array sizes and fixed errors
d) Callie Pilkington: Leader for simulations of orbits and hot or cold cases

Performance Indicator 1
(Project’s advisor will determine whether the listed tasks were completed).

Answer the following questions:

For project tasks in which I was not the leader, I provided the following inputs towards their completion:

- SolidWorks CubeSat models: Did not offer any inputs for this team goal.
- SolidWorks simulations of CubeSat: Advised against using SolidWorks for transient temperature simulations at the beginning of the spring semester. Reviewed previous research papers for groups who had similar projects and attempted to use SolidWorks without success. Moved forward with SatTherm after reading of previous successes with the software.

Performance Indicator 2
For project tasks in which you were the leader, describe the input other group members provided towards the successful completion of these tasks.

Name of Student 1: Luke Bartley

- SatTherm simulations for CubeSat: I ran into great difficulty with determining which array sizes should be used for the inputs. Ultimately, I could not correctly determine what sized the inputs should be and could not perform the simulations. Luke determined the correct array sizes and successfully ran the program, so we were able to accurately estimate the transient temperature of the satellite throughout its orbit. Did a great deal of research concerning heat transfer, finding and reviewing previous research papers for us to reference during simulations.

Name of Student 2: Lukas Hayes
• While we did not work directly together excluding the initial research necessary for the project proposal, Lukas did a great job as team lead, and helped to keep everyone on track and offered support when it was needed.

Name of Student 3: Justin Poole

• Hot and cold case parameters: While neither of us were particularly the leader for this deliverable, Justin took care of hot and cold case parameters for the SolidWorks simulations. He determined how much heat the internal components generated at full power for hot case analysis.

**Performance Indicator 4**
List all goals this project had to satisfy to be considered successfully completed.

• Maintain temperature of the etalon (or interferometer) to 25 °C with a temperature gradient of 0.1 °C
• Maintain temperature of the camera (or detector) below 0 °C

**Performance Indicator 6**
(To be addressed by the faculty advisor).

Outcome (7) An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

1. Student’s ability to find information relevant to problem solution without guidance.
2. Student’s ability to identify the additional knowledge needed to complete project.
3. Student’s ability to acquire and apply the additional knowledge needed to complete project.

**Performance Indicator 1**

Describe what information you found in order to successfully complete the tasks you were assigned in the project.

• Details about thermal paint, their characteristics related to emissivity and absorptivity.
• Reviewed different orbits and their typical inclination and right ascension of the ascending node (RAAN).
• The forms of heat transfer the satellite would receive, related to Earth IR, albedo, and solar radiation.
• Typical conditions for hot and cold cases the satellite would endure, related to the solar vector and albedo factor.
• View factor calculation and how it would impact the satellite’s thermal conditions.
• How the temperature would change relative to the amount of radiation received, the previous temperature, time spent in orbit, and time spend in eclipse.

What sources did you use to find this information?

• Information from thermal paint suppliers, related to cost, application time, and emissivity and absorptivity.
• Textbooks related to orbital mechanics.
• Textbooks related to heat transfer.
• Academic research papers related to heat transfer and thermal control within nanosatellites or CubeSats.

**Performance Indicator 2**

Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

• Proficiency with MATLAB
• Understanding of heat transfer mechanics, particularly related to radiation.
• Understanding of orbit parameters.

**Performance Indicator 3**

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

• Reviewed previous research papers that had similar goals or problems to our project.
• Gained familiarity with the basics of heat transfer, reviewed academic papers or textbooks to understand the principles.
• Researched view factors, emissivity, and absorptivity, and how these characteristics would impact the temperature of the CubeSat.
• Broke down SatTherm code into equations I could find in the textbooks referenced; this helped to understand the process of the code and how the inputs may need to be structured.
9.4. ABET Questionnaire 4 – Justin Poole

Student Name: Justin Poole

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

5. Generates a detailed statement of all the specified engineering needs for the design project.
6. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
7. Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
8. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)

Performance Indicator 1

Describe the engineering needs for this project.

Most of the engineering needs required for this project were provided by the school. Engineering needs for this project consisted of different kinds of software to carry out various simulation and analysis tasks. MATLAB was utilized for the external thermal analysis of the satellite while SOLIDWORKS flow simulation was used to determine the internal thermal analysis of the satellite and design the components of the thermal control system.

List the project goals along with performance criteria.

The goal of this project was to meet the requirements set by Michigan Aerospace Corporation. Certain internal components specified by MA had to be maintained at a certain temperature in order to maintain proper functionality. The first component that required thermal control was the etalon, where the requirement set by MA was a thermal gradient of 0.1 Celsius. Our group was able to reach a value of 0.4-0.5 Celsius but it is believed that better results are possible with a more complex simulation method. The second goal was to keep the detector below 0 Celsius, and this was achieved convincingly.

List the project constraints.

The main constraint was that the chassis must be kept at a certain size, so the size and placement of the thermal control system design was a large consideration. A second constraint was the orbit that the satellite had to be tested on. Two possible orbits were defined by MA, and each had unique levels of thermal fluctuation.
List the methods/procedures that were implemented to ensure that the customer expectations were addressed.

In order to meet the expectations of MA the testing parameters for the SOLIDWORKS simulations were set to be as close as possible to the real conditions. Theoretical calculations were also done to determine key parameters (hot and cold cases). Weekly meetings with MA were also held to make sure the correct steps were being taken.

**Performance Indicator 2**

Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health:

For this project public health and safety was not a major concern due to the nature of satellites typically being far from the public. Any aspects of the satellite that might be a concern to other satellites such as maneuvering systems or communications systems fall under tasks that would be out of the scope of our project to design a thermal control system.

Public safety:

See Public health.

Public welfare:

See Public health.

**Performance Indicator 3**

List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors:

N/A

Cultural factors:

N/A

Social factors:
Performance Indicator 4
(To be addressed by the faculty adviser).

Outcome (4) An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental and societal contexts.

Performance Indicator 2:
Student is able to make informed judgments based on the impact of engineering solutions in global, economic, environmental and societal context.

Did you adapt your project to make it useful in many countries? Y / N / NA If yes, explain:

N/A

Did you consider standards and regulations, either U.S. or international? Y / N / NA If yes, explain how they affected your project:

N/A

Did you consider the effects of manufacturing in various locations? Y / N / NA If yes, where in the report did you address this issue?
Did you have to balance effects of costs and performance?  Y / N / NA If yes, explain and refer to the report as appropriate.

N/A

Did you consider effects of maintenance, failure and repair on cost, safety, etc.?  Y / N / NA If yes, where in the report did you address them?

Yes. These are referenced in sections 5.1.3.

What were your considerations (e.g., cost, weight, manufacturing, availability, safety, recycling, etc.) in the selection of materials? List, explain and refer to the text of the report as appropriate.

Cost Considerations: Section 5.2
Weight Considerations: Section 5.3
Manufacturing Considerations: Section(s) 5.2

Does your project impact air quality, water quality, noise levels, and other environmental aspects?  Y / N / NA If yes, explain how and show what were your actions.

N/A

Does your project impact human health during manufacturing or normal use?  Y / N / NA If yes, explain what you did to alleviate the risks.

N/A

Are there any other safety issues typical to your project?  Y / N / NA If yes, explain your decisions and actions. Refer to the report as appropriate.

No.

Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives.
Performance Indicators:

7. Student’s ability to function effectively
8. Student provides task specific leadership.
9. Student creates a collaborative and inclusive environment.
10. Group establishes goals.
11. Group plans tasks

(If you copy and paste from the report, mention Section number or page numbers.)

**Performance Indicators 2 & 5**

List all tasks required to accomplish the goals of this project, and name the group member responsible for

a) Project Manager/Team Lead – Lukas Hayes
b) Research of methods of thermal control – No particular leader; Team deliverable
   i. Luke Bartley: Thermal Washers
   ii. Lukas Hayes: MLI, Thermoelectric Coolers, Radiators, False Walls
   iii. Callie Pilkington: Thermal Paint
c) Orbital parameter determination – Callie Pilkington
d) Hot and cold case parameters – Callie Pilkington, Justin Poole
   i. Callie Pilkington: Leader for hot and cold case parameters used in SatTherm
   ii. Justin Poole: Leader for hot and cold case parameters in SolidWorks
e) SolidWorks CubeSat models – Luke Bartley, Lukas Hayes, Justin Poole
   i. Luke Bartley: Simplified CubeSat Chassis Model
   ii. Lukas Hayes: Co-lead for all additional SolidWorks models and set-up of internal configurations
   iii. Justin Poole: Co-lead for all additional SolidWorks models and set-up of internal configurations
f) SolidWorks simulations of CubeSat – Lukas Hayes, Justin Poole
   i. Lukas Hayes: Leader for Cold Case Simulations
   ii. Justin Poole: Leader for Hot Case Simulations
g) SatTherm simulations of CubeSat – Luke Bartley, Callie Pilkington
   i. Luke Bartley: Leader for determination of array sizes and fixed errors
   ii. Callie Pilkington: Leader for simulations of orbits and hot or cold cases

**Performance Indicator 1**

(Project’s adviser will determine whether the listed tasks were completed).

Answer the following questions:

For project tasks in which I was **not** the leader, I provided the following inputs towards their completion:
SolidWorks Simulations of CubeSat: For the cold case simulations, I was able to help Lukas by working together to determine a logical method of iteration to converge on the desired final temperature.

SatTherm Simulations: Assisted Lukas in the documentation of the code in which we transferred the code into a runnable file while fixing syntax errors and creating a reference sheet that contained all function handles, their inputs, outputs, the variable meanings, and a description of all functions.

**Performance Indicator 3**
For project tasks in which you were the leader, describe the input other group members provided towards the successful completion of these tasks.

Name of Student 1: Luke Bartley

Luke was able to provide us with a defeatured form of the CubeSat chassis which made the simulations run much faster than the original model we received.

Name of Student 2: Lukas Hayes

Lukas was able to help me in determining logical ways to come to a desired result through constant collaboration and useful insight based on his own research and understanding. He was able to alleviate the stress from, and assist, in running thermal simulations in conjunction with my own simulations in order to obtain essential information efficiently. This information was crucial in coming to final internal configuration designs and final thermal simulation results.

Name of Student 3: Callie Pilkington

Callie was able to obtain the orbital parameters and the ambient temperatures for the hot and cold cases that were crucial for completing final simulations and final internal parameters.

**Performance Indicator 4**
List all goals this project had to satisfy to be considered successfully completed.
Performance Indicator 6
(To be addressed by the faculty adviser).

Outcome (7) An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

4. Student’s ability to find information relevant to problem solution without guidance.
5. Student’s ability to identify the additional knowledge needed to complete project.
6. Student’s ability to acquire and apply the additional knowledge needed to complete project.

Performance Indicator 1

Describe what information you found in order to successfully complete the tasks you were assigned in the project.

In order to successfully complete the tasks I was assigned in this project I had to reach out to manufacturers about specific materials for their components that would be implemented inside of the CubeSat. For material and data sheets that did not contain the necessary thermal or mechanical properties for SolidWorks, I had to contact the companies again to inquire about more specific data for the materials. If those companies failed to answer, however, I had to take the specific material composition, specifically for the material FR-110 highlighted in section 4.6.1 and calculate the composition of the needed material as a percentage of the base materials using the densities and coefficients of thermal expansion for each base material. This provided an estimated percentage which was then used to estimate the remaining thermal and mechanical properties of this material for use in the simulations.

Other information would include a full atmospheric model that provided the number density of 6 elements within the atmosphere from an altitude of 0 km to 1000 km by 50 km increments. From this data, I calculated the resulting mixed gas thermal properties based on the percent composition of the base elements.

What sources did you use to find this information?
All of this information was received via the vendor company, general data about certain materials found in textbooks, and general data made available from experimental procedures such as research papers and published journals.

**Performance Indicator 2**

Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

Right away, I needed to improve my knowledge of SolidWorks simulations and flow simulations in order to begin the largest portion of my responsibilities for this project. After this, I needed to acquire a more fundamental understanding of heat transfer to ensure the simulations produced results similar to what would be expected from calculations.

Furthermore, knowledge about atmospheric composition and radiation exposure was needed in order to properly consider and brainstorm different solutions to the proposed project.

**Performance Indicator 3**

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

For more basic and fundamental knowledge, multiple textbooks and published papers were acquired as sources of reliable information and equations. With respect to SolidWorks thermal analysis, basic simulations were set up in order to test different aspects and the effects of multiple different parameters that can be set. Further information was acquired from SolidWorks official website along with instructional videos provided by industry professionals.
10. Appendix II - SatTherm Code

10.1. Main Code

% This script is used to input all the satellite and orbit Data needed to run SatTherm
clear all
close all
c1c
%
----------------------------------------------------------
Simulation Time
delta_t=.5; %time step <s>
min=360; % Duration <min>
t_final=60*min; %Duration <s>
year=2023;
month=04;
day=18;
%
----------------------------------------------------------
-------
Orientations
orientation='Nadir';
rotation_axis='+Z'; %axis of rotation
shape='Rectangle'; %satellite shape
nodename=['2PZ';'2NZ';'6PX';'3PY';'6NX';'3NY']; %Node Names
ntot=6; %total side, 6 for rectangular
%
----------------------------------------------------------
Orbit Properties
inc=98; %Orbit Inclination <deg>
raan=0; %Right Ascension of Ascending Node <deg>
arg_peri=0; %Argument of Periapsis <degree>
max_alt=600; %Altitude above Earth <km>
ecc=.0; %eccentricity of elliptical orbit
setraddec=15; % Right Ascension and Declination, for orientaion option

% Set R.A. and Dec
%
----------------------------------------------------------
Earth and Sun Properties
Re=6378.137; %Radius of Earth <km>
mu=398601; %Earth Gravitational Parameter <km^3/s^2>
Te=249; %Earth Temperature
AF=.18; %Albedo Factor
Gs=1317; %Solar Constant <W/m^2>
RAsun=25; %Right Ascension of Sun
Decsun=20; %Declination of Sun
%
----------------------------------------------------------
Satellite Properties
A=[.02 .02 .06 .03 .06 .03]; %Surface Area of each side <m^2>
th=[.002 .002 .002 .002 .002 .002]; %thickness <m>
rhoc=[2700 2700 2700 2700 2700 2700]; %density <kg/m^3>
cp=[896 896 896 896 896 896]; %Specific Heat <J/(kg*K)>
abso_sol=[.15 .15 .15 .15 .15 .15]; %Solar Absorbtivity
emis_ir=[.91 .91 .91 .91 .91 .91]; %IR emissivity
temp_init=[295 295 295 295 295 295]; %Initial Temp (K)
temp_init(:,:,):=298;
inthl=[0 0 0 0 0 0]; %Internal Heat Load <W>
%Conductance Matrix, Contact Conductance, <W/K>
%Note: Usually given as h_c,in W/m^2-K,
%for Aluminum with milled and clean surfaces
%h_c=1730 W/m^2 K
% Contact Areas
CA=[ 0 0 0.2000 0.2000 0.2000 0.2000;  
     0 0 0.2000 0.2000 0.2000 0.2000;  
     0.2000 0.2000 0 0.6000 0 0.6000;  
     0.2000 0.2000 0.6000 0 0.6000 0;  
     0.2000 0.2000 0 0.6000 0 0.6000;  
     0.2000 0.2000 0.6000 0.6000 0 0.6000]*1e-3;  
conductance=CA.*1730;  
%
% Radiation View Factors Matrix for 3U  
% See ViewFactor_Calc.m
rad_vf=[ 0 0.0603 0.3081 0.1617 0.3081 0.1617;  
         0.0603 0 0.3081 0.1617 0.3081 0.1617;  
         0.1027 0.1027 0 0.1595 0.4756 0.1595;  
         0.1078 0.1078 0.3190 0 0.1595 0.1464;  
         0.1027 0.1027 0.4756 0.1595 0 0.1595;  
         0.1078 0.1078 0.3190 0.1464 0.3190 0];
%
%-----------------------------------------------------------------------------  
% Rotation
spins=0; % Spin per minute
a=(Re+max_alt)./(1+ecc); % Orbit semi-major axis
P=2.*pi .*sqrt(a^3/mu); % Orbit period
rotation=(360*spins)*P/60;
%-----------------------------------------------------------------------------  
% Function
Trans_Temp =
trans_temp(t_final,delta_t,shape,inc,raan,arg_peri,max_alt,ecc,orientation,setraddec,rotation,  
rotation_axis,Re,mu,Te,AF,Gs,RAsun,Decsun,ntot,A,th,rho,cp,abso_sol,emis_ir,temp_init,inthl,  
conductance,rad_vf,nodename,year,month,day);

10.2. trans_temp Function

% Calculate Transient Temperatures
function [t,temp] =
trans_temp(t_final,delta_t,shape,inc,raan,arg_peri,max_alt,ecc,orientation,setraddec,rotation,  
rotation_axis,Re,mu,Te,AF,Gs,RAsun,Decsun,ntot,A,th,rho,cp,abso_sol,emis_ir,temp_init,inthl,  
conductance,rad_vf,nodename,year,month,day)
tic
close all
V=A.*th; % Node volumes
C=rho.*V.*cp; % Node thermal capacities
sigma = 5.6704e-8; % Stefan Boltzmann constant (w/(m^2 K))
r_sun=RADec2geocen(RAsun,Decsun,149598000); % Geocentric position of sun (km)
a=(Re+max_alt)./(1+ecc); % Orbit semi-major axis
P=2.*pi .*sqrt(a^3/mu); % Orbit period
if P/delta_t <= 2.*rotation/360
disp('Warning: Aliasing may occur. The sampling rate is less than the Nyquist Rate for the  
spacecraft rotation. The time step-sizes should be decreased, or the rotation should be  
decreased. ')
end
% Radiation Network
Res_self_inv = (A.*emis_ir)./(1-emis_ir);
% R=1/(1-eps_i)/(A_i*eps_i) 
Res_other_inv = (repmat(transpose(A),1,ntot).*rad_vf);
\%1/R_{ij} = (1/A_i F_{ij}) - 1 \quad \text{Cengel Eqn. 9-49}

\text{Res}_{mat} = \text{Res}_{other}^{-1}; \quad \%\text{Begin building Resistance Network matrix}
\text{for } j=1:ntot; \quad \%\text{continue building Resistance Network Matrix}
\text{Res}_{mat}(j,j) = -\text{Res}_{self}^{-1}(j) - \text{sum} (\text{Res}_{other}^{-1}(j,:)); \\
\text{end}
\%\text{Figure out how many sides there are (outside panels)}
\text{switch shape}
\text{case 'Rectangle'}
\text{nsides} = 6;
\text{case 'Hexagon'}
\text{nsides} = 8;
\text{case 'Octogon'}
\text{nsides} = 10;
\text{otherwise}
\text{disp('Error: Invalide Shape Option.')}
\text{end}
\text{temp} = \text{reshape} (\text{temp}_{init},1,1,ntot); \%\text{set initial temp} \%\%\%\%\%\%\%\%
\text{t}_old = 0;
\text{delta} \_\text{t}_old = \text{delta}_t;
\text{k}_old = 0;
\text{N} = \text{t}_{final}/\text{delta}_t; \%\text{number of timesteps}
\%\text{initialize arrays, to be filled in the loop}
\text{l} = 1;
\text{t} = \text{zeros}(\text{floor}(\text{N}+1),1,1);
\text{r}_{sc} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{v}_{sc} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{XYZ} \_\text{geoc} = \text{zeros}(\text{floor}(\text{N}+1),3);
\text{S} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{PF} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{zloc} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{xloc} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{yloc} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{n} = \text{zeros}(\text{floor}(\text{N}+1),3,\text{ntot});
\text{n}_{inloc} = \text{zeros}(\text{floor}(\text{N}+1),3,\text{ntot});
\text{n}_{inloc \_rot} = \text{zeros}(\text{floor}(\text{N}+1),3,\text{ntot});
\text{qext \_arr} = \text{zeros}(\text{floor}(\text{N}+1),3,\text{ntot});
\text{Qext} = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{Qspace} = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{Qcond} = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{Qrad} = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{Qint} = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{latT} = \text{zeros}(\text{floor}(\text{N}+1),3,1);
\text{temp} = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{delta} \_\text{t}_lim = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\text{delta} \_\text{t}_lim \_\text{min} = \text{zeros}(\text{floor}(\text{N}+1),1,1);
\text{tcheck} \_\text{sum} = \text{zeros}(\text{floor}(\text{N}+1),1,1);
\text{delta} \_\text{t}_new = \text{zeros}(\text{floor}(\text{N}+1),1,\text{ntot});
\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\
\text{while } \text{t}_old < \text{t}_{final}
\text{k} = \text{k}_old + 1;
\text{percent} = \text{t}_old/\text{t}_{final} \times 100;
\text{t}(\text{k},:) = \text{t}_old + \text{delta}_t \_\text{old}; \%\text{current time (s)}
[r_sc(k,:), v_sc(k,:)] = geocen_rv(inc, raan, arg_peri, max_alt, ecc, t(k,:));
%*********************************************
%current position & velocity vects (km) and (km/s)
perp_2_orbit_plane = cross(r_sc(k,:), v_sc(k,:));
% a vector that is perpendicular to the plane of the orbit
S(k,:) = r_sun - r_sc(k,:);
%line of sight vector between spacecraft and sun (km)
%Define the Spacecraft local axes, xloc,yloc,zloc, in geocen-eq.
%coordinates. zloc is either sun-facing, nadir-facing, or
%star-facing. yloc is in the plane of the orbit (in direction of
%SC velocity if Nadir-facing). And yloc is orthogonal to zloc
%and xloc to form a right hand coord system,
%----------------------------------------------------------------Magnetic Field Facing
if isequal(orientation,'Magnetic') %pole facing
lat = atand(r_sc(k,3)./sqrt(r_sc(k,1).^2+r_sc(k,2).^2));
%Calculate longitude. range +/-180
%East is Positive west is negative. First determine which quadrant
%spacecraft is in.
latT(k,:)=lat;
if (r_sc(k,1)>=0)&&(r_sc(k,2)>=0)
lon=acosd(r_sc(k,1)./sqrt(r_sc(k,1).^2+r_sc(k,2).^2));
elseif (r_sc(k,1)<0)&&(r_sc(k,2)>=0)
lon=acosd(r_sc(k,2)./sqrt(r_sc(k,1).^2+r_sc(k,2).^2))+90;
elseif (r_sc(k,1)<0)&&(r_sc(k,2)<0)
lon=acosd(-r_sc(k,1)./sqrt(r_sc(k,1).^2+r_sc(k,2).^2))-180;
elseif (r_sc(k,1)>=0)&&(r_sc(k,2)<0)
lon=acosd(-r_sc(k,2)./sqrt(r_sc(k,1).^2+r_sc(k,2).^2))-90;
end
height1=sqrt(r_sc(k,1).^2+r_sc(k,2).^2+r_sc(k,3).^2);
%height above earth in km
%-------------------------------Spherical to Cartesian
% [xg, yg, zg] = sph2cart(lon*pi/180, lat2*pi/180, alt);
% XYZ_geoc1(k,1)=xg;
% XYZ_geoc1(k,2)=yg;
% XYZ_geoc1(k,3)=zg;
% % Magnetic Field Vector
% XYZ_geoc1(k,:) = XYZ_geoc1(k,:) - r_sc(k,:);
% zloc(k,:) = XYZ_geoc1(k,:) ./ norm(XYZ_geoc1(k,:));
% %SC local axes in Geocen-Eq Coords
% xloc(k,:) = cross(perp_2_orbit_plane, zloc(k,:)) ./ norm(cross(perp_2_orbit_plane, zloc(k,:)));
% yloc(k,:) = cross(zloc(k,:),xloc(k,:));
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
elseif isequal(orientation,'Sun') %sun-facing
zloc(k,:) = $\frac{S(k,:)}{\|S(k,:)|}$;
%SC local axes in Geocen-Eq Coords
xloc(k,:) = cross(perp_2_orbit_plane,zloc(k,:))./norm(cross(perp_2_orbit_plane,zloc(k,:)));
%if xloc perp to orbit plane, cross(perp_2_orbit_plane,zloc)
%is NaN. Instead define xloc in direction of vel at periapsis
if isnan(xloc(k,:))
    xloc(k,:) = $\frac{v_{sc}(l,:)}{\|v_{sc}(l,:)|}$;
end
yloc(k,:) = cross(zloc(k,:),xloc(k,:));
elseif isequal(orientation,'Nadir') %Nadir-facing
%SC local axes in geocen_eq coords
zloc(k,:) = $\frac{-r_{sc}(k,:)}{\|r_{sc}(k,:)|}$;
xloc(k,:) = $\frac{v_{sc}(k,:)}{\|v_{sc}(k,:)|}$;
yloc(k,:) = cross(zloc(k,:),xloc(k,:));
elseif isequal(orientation,'Set R.A. & Dec.') %Set-orientation
%SC local axes in geocen_eq coordinates
zloc(k,:) = $\text{RADec2geocen}(\text{setraddec}(l),\text{setraddec}(2),1)$;
xloc(k,:) = cross(perp_2_orbit_plane,zloc(k,:))./norm(cross(perp_2_orbit_plane,zloc(k,:)));
%if xloc perp to orbit plane, cross(perp_2_orbit_plane,zloc)
%is NaN. Instead define xloc in direction of vel at periapsis
if isnan(xloc(k,:))
    xloc(k,:) = $\frac{v_{sc}(l,:)}{\|v_{sc}(l,:)|}$;
end
yloc(k,:) = cross(zloc(l,:),xloc(l,:));
else
    disp('Error: Invalid Orientation Option.');
    break
end
%Define the normals for all side surfaces
%Initial Orientation: local axes in SC local coords
xloc_inloc = $[1,0,0]$;
yloc_inloc = $[0,1,0]$;
zloc_inloc = $[0,0,1]$;
%rotation matrix to convert from local coords to geocen-eq coords
M = [xloc_inloc;yloc_inloc;zloc_inloc]\[xloc(k,:);yloc(k,:);zloc(k,:)];
%normal vectors in SC local coords
n_inloc(k,:,1) = zloc_inloc;
n_inloc(k,:,2) = -n_inloc(1,:,1);
n_inloc(k,:,3) = xloc_inloc;
for j=l:ntot %loop through nodes
    if j <= nsides %outside panels
        if j >= 4
            side_ang = 360./(nsides-2); %side angles (deg)
            n_inloc(k,:,j) = rot3(n_inloc(k,:,3),(j-3)*side_ang,0);
        end
    end
%Additional Rotation
%NOTE: rotating the normals, but not the
%local axes means that you can only do rotation about
%one axis at a time.
rotat=rotation.*t(k)./P;
switch rotation_axis
 case '+X'
  n_inloc_rot(k,:,j)=rotl(n_inloc(k,:,j),rotat);
 case '+Y'
  n_inloc_rot(k,:,j)=rot2(n_inloc(k,:,j),rotat);
 case '+Z'
  n_inloc_rot(k,:,j)=rot3(n_inloc(k,:,j),0,rotat);
 otherwise
  disp('Error: Invalid Rotation Axis Option.')
end
%convert normal vectors from local coords back
%to geocen-eq. coords
n(k,:,j) = n_inloc_rot(k,:,j)*M;

%%%%Calculate Heat Flow%%%%%
%environmental radiation flux [qs,qa,qe] (W/m~2)
q_ext_arr(k,:,j) = ext_heat_flux_loop(r_sc(k,:),r_sun,n(k,:,j),Gs,AF,Te,abso_sol(j),emis_ir(j));

%environmental radiation input on the node (W)
Q_ext(k,:,j)=A(j).*sum(q_ext_arr(k,:,j),2);
Q_space(k,:,j)=A(j).*emis_ir(j).*sigma*(0-temp_old(:,:, j ).^4);
else
%Now for the inside objects
  Q_ext(k,:,j) = 0;
  Q_space(k,:,j) = 0;
end
%array of the node temp, differences (linear and 4th power)
temp_dif_mat = reshape((temp_old-temp_old(:,j,:)), l,ntot);
temp4_dif_mat = reshape((temp_old.^4-(temp_old(:,:,j)).^4),l,ntot);
%Conduction Heat flow
Qcond(k,:,j) = sum(conductance(j,:).*temp_dif_mat);

%Radiation Network
E_mat = transpose(sigma.*(reshape(temp_old,1,ntot)).^4.*Res_self_inv);
J_mat = Res_mat*(-E_mat);
Q_rad(k,:,j)=sum(transpose(J_mat-J_mat(j,:)).*Res_other_inv(j,:));
%Radiative heat Cengel Eq9-50
Q_int(k,:,j)=inthl(j); %Internal Heat source

%Check time-step for stability

tcheck_cond = 1./C(j).*conductance(j,:);
ind = find(temp_dif_mat==0);
tcheck_rad =1./C(j).*(transpose(J_mat-J_mat(j,:)).*Res_other_inv(j,:))/(temp_dif_mat);
tcheck_rad(ind) = 0;
tcheck_ext = 1./C(j).*Q_ext(k,:,j)./temp_old(:,j,:);
tcheck_space = 1./C(j).*Q_space(k,:,j)./(-temp_old(:,j,:));
tcheck_sum(k,:,j) = sum(tcheck_cond)+sum(abs(tcheck_rad)+sum(tcheck_ext)+sum(tcheck_space);
delta_t_lim(k,:,j) = 1./tcheck_sum(k,:,j);
end
delta_t_lim_min(k) = min(delta_t_lim(k,:,:));
if delta_t > delta_t_lim_min(k) %if time-step too large
    delta_t_new = 0.9.*delta_t_lim_min(k);
else
    delta_t_new = delta_t;
end

%New temperatures
temp(k,:,:,:) =
    temp_old(:,:,1)+delta_t ./ (reshape(C,l,l,ntot)) .* (Qext(k,:,:)+Qspace(k,:,:)+Qcond(k,:,:)+Qrad(k,:,:)+Qint(k,:,:));
%Advance for next time loop
    t_old=t(k,:);
    delta_t_old = delta_t_new;
    temp_old = temp(k,:,:);
    k_old = k;
end
for h=1:nsides
    %Plot external radiation on each side
    figure(h)
    plot(t(1:N-1)./60^2,qext_arr(1:N-1,1,h),'r')
    hold on
    plot(t(1:N-1)./60^2,qext_arr(1:N-1,2,h),'b')
    plot(t(1:N-1)./60^2,qext_arr(1:N-1,3,h),'g')
    plot(t(1:N-1)./60^2,sum(qext_arr(1:N-1,:,:),2),'k')
    legend('Solar','Albedo','Earth IR','Total')
    xlabel('Time (hrs)')
    ylabel('[nodename(h,:), Environmental Heat Flux (W/m^2)]')
end
%Plot the temperature of each node
    cell(l,ntot);
    col=repmat([['r','g','b','c','m','y','k'] ,1,37],1,37);
    figure(h+1)
    for hh=1:ntot
        plot(t(1:N-1)./60^2,temp(1:N-1,:,hh),col(hh))
        hold on
        leg=zeros(ntot,3);
        leg(hh,:)=nodename(hh,:);
    end
    xlabel('Time ( hrs) ')
    ylabel('Temperature (K)')
    legend('2PZ','2NZ','6PX','3PY','6NX','3NY')
    hold off
%Reshape temp array for output in 2D matrix form
S=size(temp);
    temp=reshape(temp,S(l),S(3));
%-------------------------------------------------------------------Orbit Graphic
figure
%------------------------Plot Orbit
plot3(r_sc(:,1),r_sc(:,2),r_sc(:,3),'g','linewidth',5)
    hold on
%--------------------------Normal to +Z Face
x_sc=zloc(1:40:N,1);
y_sc=zloc(1:40:N,2);
z_sc=zloc(1:40:N,3);

%spacecraft Location
x_scp=r_sc(1:40:N,1);
y_scp=r_sc(1:40:N,2);
z_scp=r_sc(1:40:N,3);
quiver3(x_scp,y_scp,z_scp,x_sc,y_sc,z_sc,4,'r')

%----------------
Plot vector in Sun Direction
sun_vec=r_sun(1,:);
us=(sun_vec./norm(sun_vec))*20000;
quiver3(0,0,0,us(1),us(2),us(3),'c','linewidth',3)
legend('Orbit Path','Direction Normal to NanoSat Face','Sun Direction')

%----------------
Plot vector in Sun Direction
sun_vec=r_sun(1,:);
us=(sun_vec./norm(sun_vec))*20000;
quiver3(0,0,0,us(1),us(2),us(3),'c','linewidth',3)
legend('Orbit Path','Direction Normal to NanoSat Face','Sun Direction')

%-----------------------
plot a globe.
Lcheck=license('test', 'MAP_Toolbox');
if Lcheck==0
[xy,z] = sphere(50);
r =6378.137 ;
surf( r*x, r*y, r*z )
axis equal
else
load topo;
axesm('globe', 'Geoid', Re)
meshm(topo, topolegend); demcmap(topo);
% Set the plot background to black.
set(gcf, 'color', 'k');
axis off;
end
toc
end

10.3. **RADec2geocen Function**

```matlab
function r_sun = RADec2geocen(RAsun,Decsun,r)
    ys=r*sind(RAsun)*cosd(Decsun);
    xs= r*cosd(RAsun)*cosd(Decsun);
    zs=r*sind(Decsun);
    r_sun = [xs ys zs];
end
```

10.4. **geocen_rv Function**

```matlab
function [r_geocen,v_geocen] = geocen_rv(inc,raan,arg_peri,max_alt,ecc,t)
%this function calculates the geocentric position of a
%spacecraft in Earth orbit.
```
%Output is a 3 element matrix
%[r1,rj,rk] in km.

%Inputs:
%inc = inclination (deg),
%raan = right ascension of ascending node (deg)
%arg_peri = argument of periapsis (deg)
%max_alt = maximum altitude (km),
%ecc = eccentricity
%t = time (s) (assuming t=0s when ecc. anom., E=0)

%Constants
mu = 398601;  %Earth's grav. parameter (km)
Re = 6378.14;  %radius of Earth (km)
a = (Re+max_alt)./(1+ecc);  %semi-major axis (km)

incr = inc.*pi./180;  %inclination (rad)
raanr = raan.*pi./180;  %raan (rad)
arg_perir = arg_peri.*pi./180;  %arg of periapsis (rad)
P = 2.*pi.*sqrt(a^3/mu);  %Orbit Period (s)
M = 2.*pi.*t./P;  %Mean Anomoly (radians)
E_guess = (M.*(1-sin(M+ecc))+(M+ecc).*sin(M))/(1+sin(M)-sin(M+ecc));

E = fzero(functE,E_guess);  %Ecc Anomoly (rads)

r_pfmag = a.*[(cos(E)-ecc),(sqrt(1-ecc.^2).*cos(E)),0];  %distance from focus (peri-focal coords) (BMW eqn 4.2-14)

v_pf = sqrt(mu.*a)./r_pfmag.*[-sin(E), sqrt(1-ecc.^2).*cos(E),0];
%rotation matrix (transform from peri-focal to geocentric coords)

rotmat(1,1) = cos(raanr).*cos(arg_perir)-sin(raanr).*sin(arg_perir).*cos(incr);
rotmat(1,2) = -cos(raanr).*sin(arg_perir)-sin(raanr).*cos(arg_perir).*cos(incr);
rotmat(1,3) = sin(raanr).*sin(incr);
rotmat(2,1) = sin(raanr).*cos(arg_perir)+cos(raanr).*sin(arg_perir).*cos(incr);
rotmat(2,2) = -sin(raanr).*sin(arg_perir)+cos(raanr).*cos(arg_perir).*cos(incr);
rotmat(2,3) = -cos(raanr).*sin(incr);
rotmat(3,1) = sin(arg_perir).*sin(incr);
rotmat(3,2) = cos(arg_perir).*sin(incr);
rotmat(3,3) = cos(incr);

r_geocen = transpose(rotmat*transpose(r_pf));  %sc position (geocentric coords)(BMW p83)
v_geocen = transpose(rotmat*transpose(v_pf));  %sc velocity (geocentric coords)

10.5.  ext_heat_flux_loop Function

function qtot = ext_heat_flux_loop(r_sc,r_sun,n,Gs,AF,Te,abso_sol,emis_ir)
%This function calculates the external (direct solar, qs, albedo
%radiation, qa and Earth IR) heat flux (W/m^2) absorbed by each
%input surface. The output is a 1 x 3 x nsides vector, where nsides
%is defined below. Each page of the output vector corresponds to
%one of the sides of the spacecraft. The 3 columns correspond to
%[qs,qa,qe] respectively. The total heat flux would be sum(output),
%and the total heat flow absorbed by the surface (W) would be sum
%(output)*area of the surface.

%Inputs:
%r_sc = surf, position geocentric-equitorial coords [rx,ry,rz]) (Km)
%r_sun = position of the sun in geocentric coords [rx,ry,rz] (km)
%n = normal vector of surface in geocentric coords [nx,ny,nz]
%Gs = solar constant (W/m^2)
%AF = Albedo Factor
%Te = Effective BB temperature of Earth (K)
%abso_sol = solar absorptivity of surface (unitless)
%emis_ir = Infrared emissivity of surface (unitless)

%Constants
sigma = 5.6704e-8; %Steffan Boltzmann const (W/(m^2 K))
Re = 6378.14; %radius of Earth (km)
sizen = size(n); %dimensions of the surfaces' normals matrix
nsides = 1; %the # of pages of n = # of surfaces
qtot = zeros(1,3,nsides); %pre-alocate, to be filled in loop

for k=1:nsides
    h = norm(r_sc)-Re; %SC altitude
    gammar = acos(-sum(n(:,:,k).*r_sc)./(norm(n(:,:,k)).*norm(r_sc)));
    gamma = gammar.*180./pi; %angle between n and r_sc in deg
    Fsce = view_factor_scearth(h,gamma); %view factor between Earth and surface
    S = r_sun-r_sc; %line of sight vector between sc and sun (km)
    psir = acos(sum(n(:,:,k).*S)./(norm(n(:,:,k)).*norm(S))); %angle between line of sight vector and surface normal
    thetar = acos(sum(r_sun.*r_sc)./(norm(r_sun).*norm(r_sc))); %Solar reflection angle off earth (radians)
    qs = Gs.*abso_sol.*cos(psir); %Direct Solar radiation absorbed by sc per sqm meter
    qa = Gs.*AF.*Fsce.*abso_sol.*cos(thetar); %Reflected Solar (albedo) radiation absorbed by sc W/m^2
    qe = sigma.*Te.^4.*emis_ir*Fsce; %Direct Earth IR radiation absorbed by sc (W/m^2)
    if insun(r_sc,r_sun)==0 %If in eclipse:
        qs = 0; %overwrite qs to zero
        qa = 0; %overwrite qa to zero
    end
    if psir >= pi/2 %If surface pointing away from sun:
        qs = 0; %overwrite qs to zero
    end
    if qa < 0 %albedo goes to zero for theta>pi/2
        qa = 0;
    end
end
%output environmental radiation absorbed by surface (W/m^2)
qtot(:,:,k) = [qs,qa,qe];
end
end

10.6. view_factor_scearth Function

function Fe = view_factor_scearth(h,gamma)
%This function calculates the view factor (also known as configuration factor, geometry factor) Fd1-2, from an infinitesimal surface (d1) to the Earth (2). Output, Fe, is unitless.

%Inputs:
%h = altitude of the surface above Earth's surface (km)
%gamma = angle between normal vector and nadir vector (degrees)

gammar = gamma.*pi./180; %gamma in radians
Re = 6378.14; %Radius of the Earth (km)
rsc = Re+h; %distance of spacecraft from center of Earth (km)

H = rsc./Re;
phi_m = asin(1./H);
b = sqrt(H.^2-1);

%if full Earth is visible to the plate
if gammar <= pi./2-phi_m
    Fe = cos(gammar)./H.^2;
%if part of the Earth is visible to the plate
else if gammar > pi/2-phi_m & gammar <= pi/2+phi_m
    tl = 1./2.*asin(b./(H.*sin(gammar)));
    t2 = 1./(2.*H.^2).*(cos(gammar).*acos(-b.*cot(gammar))-b.*sqrt(1-H.^2.*(cos(gammar))^2));
    Fe = 2./pi.*(pi./4-tl+t2);
%if none of the Earth is visible to the plate
else
    Fe = 0;
end
end

10.7. insun Function

function insun = insun(r_sc,r_sun)
%This function determines whether a spacecraft is in sunlight (returning 1) or in eclipse (returning 0) given the inputs:
%r_sc = spacecraft position in geocentric coords(km)
%r_sun = sun position in geocentric coords (km)
Re  = 6378;  %radius of Earth (km)
theta1 = acos(Re./norm(r_sc));  %angle (see note book p29a) (rads)
theta2 = acos(Re./norm(r_sun));  %angle (see note book p29a) (rads)
psi    = acos(sum(r_sc.*r_sun)./(norm(r_sc).*norm(r_sun)));  
%angle between sc position vector and sun position vector (rad)
%if psi is <= thetal+theta2, its in sun, otherwise its in eclipse
if psi >= thetal+theta2;
    insun  = 0;
else
    insun  = 1;
end
end

10.8.  rot3 Function

function [norm_vector]=rot3(initial,alpha,beta)
%initial: reference normal vector at given time
%alpha: rotation to orientate matrix to face in counterclockwise direction
%beta:angle of rotation
ROT1=[cosd(alpha) sind(alpha) 0; -sind(alpha) cosd(alpha) 0; 0 0 1];
new_normal_2_face=initial'
\ROT1;
ROT2=[cosd(beta) sind(beta) 0; -sind(beta) cosd(beta) 0; 0 0 1];
norm_vector=new_normal_2_face'
\ROT2;
end

10.9.  ViewFactor_Calc

VF = zeros(6,6);

% View Factors Perpendicular Rectangle with Common Edge
% X to Z - Works

h = 0.03;  % side [m]
w = 0.01;  % side [m]
l = 0.02;  % side [m]
H = h/l;
w = w/l;
h2 = H^2;
w2 = W^2;

f1 = w.atan(1/w);
f2 = H.atan(1/H);
f3 = sqrt(h^2+w^2).atan(1/(sqrt(h^2+w^2)));
f4 = ((1+w^2)*(1+h^2))/(1+w^2*h^2);
f5 = (w^2*(1+w^2*h^2))/((1+w^2)*(w^2+h^2));
f6 = (h^2*(1+h^2+w^2))/((1+h^2)*(h^2+w^2));
F1 = (1/(pi*w))*(f1+f2-f3+(0.25*log(f4*(f5+w^2)*(f6+h^2)))))
VF(1:2,3) = F1;
VF(1:2,5) = F1;

% View Factors Perpendicular Rectangle with Common Edge  
% Z to X - Works

h = 0.01; % side [m]
w = 0.03; % side [m]
l = 0.02; % side [m]
H = h/l;
w = w/l;
h2 = H*l2;
w2 = W*l2;

f1 = W*atan(1/w);
f2 = H*atan(1/H);
f3 = sqrt(h2+w2)*atan(1/(sqrt(h2+w2)));
f4 = ((1+w2)*(1+h2))/(1+w2+h2);
f5 = (w2*(1+w2+h2))/((1+w2)*(w2+h2));
f6 = (h2*(1+h2+w2))/((1+h2)*(h2+w2));
F2 = (1/(pi*W))*(f1+f2-f3+(0.25*log(f4*(f5*w2)*(f6*h2))))
VF(3,1:2) = F2;
VF(5,1:2) = F2;

% View Factors Perpendicular Rectangle with Common Edge  
% Sides, Z to Y - Works

h = 0.03; % side [m]
w = 0.02; % side [m]
l = 0.01; % side [m]
H = h/l;
w = w/l;
h2 = H*l2;
w2 = W*l2;

f1 = W*atan(1/w);
f2 = H*atan(1/H);
f3 = sqrt(h2+w2)*atan(1/(sqrt(h2+w2)));
f4 = ((1+w2)*(1+h2))/(1+w2+h2);
f5 = (w2*(1+w2+h2))/((1+w2)*(w2+h2));
f6 = (h2*(1+h2+w2))/((1+h2)*(h2+w2));
F3 = (1/(pi*w))*((f1+f2-f3+(0.25*log(f4*(f5*w2)*(f6*h2)))))
VF(1:2,4) = F3;
VF(1:2,6) = F3;

% View Factors Perpendicular Rectangle with Common Edge  
% Sides, Y to Z - Works

h = 0.02; % side [m]
w = 0.03; % side [m]
\[ l = 0.01; \% \text{side [m]} \]
\[ H = h/l; \]
\[ w = w/l; \]
\[ h2 = H^2; \]
\[ w2 = W^2; \]

\[ f1 = \frac{w\times\arctan(1/w)}{l}; \]
\[ f2 = \frac{H\times\arctan(1/H)}{l}; \]
\[ f3 = \sqrt{(h^2+w^2)}\times\arctan\left(\frac{1}{\sqrt{(h^2+w^2)}}\right); \]
\[ f4 = \frac{(1+w^2)(1+h^2)/(1+w^2+h^2)}{l}; \]
\[ f5 = \frac{(w^2(1+w^2+h^2))/(1+w^2)(w^2+h^2)}{l}; \]
\[ f6 = \frac{(h^2(1+h^2+w^2))/(1+h^2)(h^2+w^2)}{l}; \]
\[ F4 = \frac{1}{\pi \times W} \times \left( f1 - f2 - f3 + (0.25\times\log(f4\times(f5^w^2)\times(f6^h^2))) \right) \]

\[ VF(4,1:2) = F4; \]
\[ VF(6,1:2) = F4; \]

\% View Factors Perpendicular Rectangle with Common Edge
\% Sides, X to Y

\[ h = 0.01; \% \text{side [m]} \]
\[ w = 0.02; \% \text{side [m]} \]
\[ l = 0.03; \% \text{side [m]} \]
\[ H = h/l; \]
\[ w = w/l; \]
\[ h2 = H^2; \]
\[ w2 = W^2; \]

\[ f1 = \frac{w\times\arctan(1/w)}{l}; \]
\[ f2 = \frac{H\times\arctan(1/H)}{l}; \]
\[ f3 = \sqrt{(h^2+w^2)}\times\arctan\left(\frac{1}{\sqrt{(h^2+w^2)}}\right); \]
\[ f4 = \frac{(1+w^2)(1+h^2)/(1+w^2+h^2)}{l}; \]
\[ f5 = \frac{(w^2(1+w^2+h^2))/(1+w^2)(w^2+h^2)}{l}; \]
\[ f6 = \frac{(h^2(1+h^2+w^2))/(1+h^2)(h^2+w^2)}{l}; \]
\[ F5 = \frac{1}{\pi \times W} \times \left( f1 + f2 - f3 + (0.25\times\log(f4\times(f5^w^2)\times(f6^h^2))) \right) \]

\[ VF(3,4) = F5; \]
\[ VF(3,6) = F5; \]
\[ VF(5,4) = F5; \]
\[ VF(5,6) = F5; \]

\% View Factors Perpendicular Rectangle with Common Edge
\% Sides, Y to X

\[ h = 0.02; \% \text{side [m]} \]
\[ w = 0.01; \% \text{side [m]} \]
\[ l = 0.03; \% \text{side [m]} \]
\[ H = h/l; \]
\[ w = w/l; \]
\[ h2 = H^2; \]
\[ w2 = W^2; \]
\[ f_1 = W \cdot \arctan(1/W); \]
\[ f_2 = H \cdot \arctan(1/H); \]
\[ f_3 = \sqrt{(h2+w2)} \cdot \arctan(1/(\sqrt{h2+w2})); \]
\[ f_4 = ((1+w2)/(1+h2))/(1+w2+h2); \]
\[ f_5 = (w2/(1+w2+h2))/((1+w2)/(w2+h2)); \]
\[ f_6 = (h2/(1+h2+w2))/((1+h2)/(h2+w2)); \]
\[ F_6 = (1/(\pi \cdot W)) \cdot (f_1 + f_2 - f_3 + (0.25 \cdot \log(f_4 \cdot (f_5^{w2}) \cdot (f_6^{h2})))) \]

\[ VF(4,3) = F_6; \]
\[ VF(4,5) = F_6; \]
\[ VF(6,3) = F_6; \]
\[ VF(6,5) = F_6; \]

% View Factors for Parallel Rectangles
% Sides, Z - Works

\[ a = 0.02; \text{ % side [m]} \]
\[ b = 0.01; \text{ % side [m]} \]
\[ c = 0.03; \text{ % distance} \]
\[ X = a/c; \]
\[ Y = b/c; \]
\[ x2 = X^2; \]
\[ y2 = Y^2; \]
\[ f_1 = \sqrt{((1+x2)/(1+y2))/(1+x2+y2)}; \]
\[ f_2 = X \cdot \sqrt{1+y2} \cdot \arctan(X/\sqrt{1+y2}); \]
\[ f_3 = Y \cdot \sqrt{1+x2} \cdot \arctan(Y/\sqrt{1+x2}); \]
\[ f_4 = X \cdot \arctan(X); \]
\[ f_5 = Y \cdot \arctan(Y); \]
\[ F_7 = (2/(\pi \cdot X \cdot Y)) \cdot (\log(f_1) + f_2 + f_3 - f_4 - f_5) \]

\[ VF(1,2) = F_7; \]
\[ VF(2,1) = F_7; \]

% View Factors for Parallel Rectangles
% Sides, X - Works

\[ a = 0.02; \text{ % side [m]} \]
\[ b = 0.03; \text{ % side [m]} \]
\[ c = 0.01; \text{ % distance} \]
\[ X = a/c; \]
\[ Y = b/c; \]
\[ x2 = X^2; \]
\[ y2 = Y^2; \]
\[ f_1 = \sqrt{((1+x2)/(1+y2))/(1+x2+y2)}; \]
\[ f_2 = X \cdot \sqrt{1+y2} \cdot \arctan(X/\sqrt{1+y2}); \]
\[ f_3 = Y \cdot \sqrt{1+x2} \cdot \arctan(Y/\sqrt{1+x2}); \]
\[ f_4 = X \cdot \arctan(X); \]
\[ f_5 = Y \cdot \arctan(Y); \]
\[ F_8 = (2/(\pi \cdot X \cdot Y)) \cdot (\log(f_1) + f_2 + f_3 - f_4 - f_5) \]
VF(3,5) = F8;
VF(5,3) = F8;

% View Factors for Parallel Rectangles
% Sides, Y - Works

a = 0.01; % side [m]
b = 0.03; % side [m]
c = 0.02; % distance
X = a/c;
Y = b/c;
x2 = X^2;
y2 = Y^2;

f1 = sqrt(((1+x2)*(1+y2))/(1+x2+y2));
f2 = X*sqrt(1+y2)*atan(X/sqrt(1+y2));
f3 = Y*sqrt(1+x2)*atan(Y/sqrt(1+x2));
f4 = X*atan(X);
f5 = Y*atan(Y);
F9 = (2/(pi*X*Y))*(log(f1)+f2+f3-f4-f5);
VF(4,6) = F9;
VF(6,4) = F9;

VF
ZPR = sum(VF(1,:))
ZNR = sum(VF(2,:))
XPR = sum(VF(3,:))
YPR = sum(VF(4,:))
XNR = sum(VF(5,:))
YNR = sum(VF(6,:))
## 11. Appendix III – Decision Matrix

<table>
<thead>
<tr>
<th>Thermal Solutions</th>
<th>Weight</th>
<th>Space</th>
<th>Cost</th>
<th>Power Consumption</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLI (Multi-Layer Insulation)</td>
<td>80</td>
<td>24</td>
<td>90</td>
<td>27</td>
<td>50</td>
</tr>
<tr>
<td>Thermal Coating</td>
<td>90</td>
<td>27</td>
<td>90</td>
<td>27</td>
<td>40</td>
</tr>
<tr>
<td>Optical Solar Reflector (OSR)</td>
<td>60</td>
<td>18</td>
<td>70</td>
<td>21</td>
<td>40</td>
</tr>
<tr>
<td>Heat Pipes</td>
<td>30</td>
<td>9</td>
<td>30</td>
<td>9</td>
<td>60</td>
</tr>
<tr>
<td>Doublers</td>
<td>30</td>
<td>9</td>
<td>10</td>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>Thermal Fillers</td>
<td>50</td>
<td>15</td>
<td>80</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>Thermal Washers</td>
<td>80</td>
<td>24</td>
<td>80</td>
<td>24</td>
<td>80</td>
</tr>
<tr>
<td>Heater (Such as Patch Heaters)</td>
<td>90</td>
<td>27</td>
<td>90</td>
<td>27</td>
<td>80</td>
</tr>
<tr>
<td>Thermoelectric Coolers</td>
<td>60</td>
<td>18</td>
<td>70</td>
<td>21</td>
<td>70</td>
</tr>
<tr>
<td>Cold Plates (Active and Passive Options)</td>
<td>30</td>
<td>9</td>
<td>60</td>
<td>18</td>
<td>70</td>
</tr>
<tr>
<td>Louvers</td>
<td>40</td>
<td>12</td>
<td>40</td>
<td>12</td>
<td>30</td>
</tr>
</tbody>
</table>

*Table 11.1: Decision Matrix*
### 12. Appendix IV – Gantt Chart

#### Thermal Control for Miniaturized Interferometer for Monitoring Airglow from a CubeSat

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>PLAN START (Date)</th>
<th>PLAN DURATION (Days)</th>
<th>ACTUAL START (Date)</th>
<th>ACTUAL DURATION (Days)</th>
<th>PROGRESS</th>
<th>PERCENT COMPLETE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research</td>
<td>1/19</td>
<td>95</td>
<td>10/9</td>
<td>147</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Proposal Presentation</td>
<td>1/17</td>
<td>14</td>
<td>11/7</td>
<td>14</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Design Thermal Solutions</td>
<td>1/17</td>
<td>28</td>
<td>11/7</td>
<td>28</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Final Proposal Report</td>
<td>1/11</td>
<td>28</td>
<td>11/1</td>
<td>28</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Figure out how to simulate</td>
<td>1/3</td>
<td>28</td>
<td>1/16</td>
<td>30</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Preliminary Design</td>
<td>1/2</td>
<td>28</td>
<td>1/5</td>
<td>45</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Detail Design</td>
<td>1/10</td>
<td>42</td>
<td>2/17</td>
<td>30</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Material Research</td>
<td>1/2</td>
<td>58</td>
<td>12/12</td>
<td>25</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Subcomponents</td>
<td>12/18</td>
<td>42</td>
<td>2/10</td>
<td>30</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Thermal Simulations</td>
<td>12/18</td>
<td>77</td>
<td>13/31</td>
<td>108</td>
<td>✔️</td>
<td>100%</td>
</tr>
<tr>
<td>Final Design Presentation</td>
<td>1/13</td>
<td>42</td>
<td>4/5</td>
<td>14</td>
<td>✔️</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Table 12.1: Gantt Chart*
13. Appendix V - Project Member Resumes


LUKE BARTLEY
Kalamazoo, MI | luke.m.bartley@vmich.edu | (248) 679-6553 | linkedin.com/in/luke-bartley

EDUCATION
Bachelor of Science, Aerospace Engineering
Western Michigan University, Kalamazoo MI
College of Engineering and Applied Sciences

EXPECTED GRADUATION - MAY 2023

EXPERIENCE
Micro-LAM
Portage, MI
Tooling Department Intern
- Developed parametric model of product in CAD software to reduce lead times for new product orders
- Facilitated research project to streamline product refurbishment process
- Drafted process, calibration, and operation documents to define concrete methods and promote knowledge transfer among the tooling department
- Broadened skills in all facets of tooling department to be able to provide assistance in all processes

May 2022 - Present

WMU Formula SAE Team
Western Michigan University
Package Validation Engineer (August 2021 - August 2022)
- Organized proper sensor selection for aero package data acquisition
- Documented methods of aero package validation and sensor installation/application
- Collaboration with CFD simulation designer to match simulations to validation
Aerodynamics Sub-Team Member (December 2019 - Present)
- Contributed to the manufacturing process of composite aero elements (carbon layups, mold making, machining)
- Familiarized with various software (Solidworks, STAR-CCM+, AutoCAD)
- Exposure to working on a project in a large team environment
- Developed specialized components to improve car performance within regulations

December 2019 - Present

Amazon
Pontiac, MI
Warehouse Associate
- Rigorous third shift schedule on the weekend
- Quickly absorbed knowledge on how to perform multiple inbound processing jobs
- High speed and physically demanding environment

June 2021 - August 2021

RELEVANT PROFICIENCIES
CAD software (Solidworks, AutoCAD, NX) Sim. software (STAR-CCM+) Other software (LabVIEW, MATLAB) Working in a team environment Microsoft Office Suite Willingness to learn

VOLUNTEERING AND HONORS
- 50+ hours of community service at soup kitchens, local homes, trash clean-ups, fundraisers
- WMU Dean’s List, WMU Achievement Award, WMU Brown & Gold Scholarship
Lukas Hayes
Phone: (989)912-0757 Email: lukas.g.hayes@wmich.edu

Objective
Enthusiastic and motivated engineering student with a strong work ethic seeking full-time for December of 2023. Offering prior engineering skills in MATLAB and CAD, self-discipline, and innovative thinking to improve and develop products.

Education
Bachelor of Science in Aerospace Engineering Graduation: Dec 2023
Western Michigan University (WMU) Kalamazoo, MI
Lee Honors College (WMU) Present

Related Experience
Senior Design Project Team Lead | WMU | Kalamazoo, MI August 2022-Present
- Managed the team’s progress
- Use thermal simulations to analyze CubeSat project
- Communicate with senior engineers and faculty mentors
- Design thermal protective devices

Co-op | Walbro | Cass City, MI October 2018-August 2019
- Developed and analyzed two new products
- Collaborated with senior engineers
- Set up instrumentation to ensure product requirements.

Quality | CJ Machine | Cass City MI November 2015–October 2018
- Inspected and tested products to meet specifications provided
- Prepared products for shipment to customers.

Other Experience
Office Manager | Eldridge Fox/Britton Hadley WMU | Kalamazoo, MI August 2020-Present
- Customer service
- Assistant to the hall director
- Handle mail and packages

Front Desk | Eldridge Fox WMU | Kalamazoo, MI August 2019-March 2020
- Customer service
- Give access to the building

Awards & Acknowledgements
Dean's List (2019-2020)
Vice President of Metal Pandemonium (2021-Present)
Resume – Callie Pilkington

Callie Pilkington
Kalamazoo, MI | (734) 771-6648 | callie.e.pilkington@wmich.edu | linkedin.com/in/callie-pilkington

Objective
A dynamic and devoted senior, always looking for opportunities to learn and develop skills. Experienced with leadership roles, group communication, multitasking objectives, public speaking, and job adaptation. Looking for a work experience that will always be supportive and teaching something new.

Education
Bachelor of Science in Aerospace Engineering Aug 2019 - Expected Graduation April 2023
- Western Michigan University (WMU), Kalamazoo, MI
- GPA: 3.91, Expected Summa Cum Laude

Work Experience
Project Management Intern | Vibracoustic, South Haven, MI Sept 2022 - Present
- Managed projects for Stellantis and Emerging OEMs Mounts division, planning production in 3 plants with estimated sales of up to 19 million Euros per year.
- Responsible for project success through acquisition, design, Industrialization, and production.
- Organized weekly reviews with eight departments to define project schedules spanning 3 years.
- Led project reviews to upper management, including Head of Sales and Regional President.
- Adapted to new PM software implementation and assisted coworkers with use and functions.

Application Team Intern | Vibracoustic, South Haven, MI May 2022 - Aug 2022
- Analyzed test results for customer reports and implemented part kickoffs.
- Assessed current inventory system and reported over 300 thousand USD of parts misplaced within a year, primarily due to inefficient system and lack of enforcement.
- Designed future routes to improve efficiency and inventory system security. Competed with fellow interns and received a company award for this project.

Student Ambassador | Office of Admissions, Western Michigan University Jan 2021 - Sept 2022
- Engaged with prospective students and families through main campus tours.
- Tailored each tour to the students’ interests and their prospective majors.
- Memorized an hour-long script and modified it with my personal stories and information.

Honors and Awards
- WMU Presidential Medallion Scholarship
- WMU Dean’s List Recipient, awarded for each semester in attendance.
- Arthur H. Hupp Endowed Memorial Scholarship

Extracurriculars and Activities
- WMU Lee Honors College, Member Aug 2019 - Present
- Alpha Lambda Delta Honors Society, Member Feb 2020 - Present
- Fighting Ignorance and Rape through Education, Peer Educator Sept 2020 - Present
- Tau Beta Pi Honors Society, Member Dec 2021 - Present
- WMU Title IX Committee, Student Representative Aug 2022 - Present
- El Concilio, English Second Language (ESL) Tutor Nov 2022 - Present
Justine Poole
Kalamazoo, Michigan | justin.matt.poole@gmail.com | (269) 359-5735 | linkedin.com/in/justin-poole-ae

Dedicated Aerospace Engineering senior with a strong work ethic seeking opportunities for professional growth and development. Offering leadership experience, ability to multitask in a fast-paced environment, CAD knowledge, and the aptitude to actively learn and adapt to the job.

EDUCATION
Western Michigan University, Kalamazoo, MI
Bachelor of Science, Aerospace Engineering,
Minor, Mathematics | GPA: 3.81 | Magna Cum Laude
Relevant coursework in propulsion II, thermodynamics II, control systems, orbital dynamics, advanced aerodynamics, aircraft design, flight test engineering, and aero structural design

EXPERIENCE
Senior Design Project, CAD/Simulation Co-lead Fall 2022 – Spring 2023
• Thermal Control for a Miniaturized Fabry–Perot Interferometer in a CubeSat
Stryker, Mechanical Engineering Intern May 2022 – October 2022
• Designed a device to optimize the service procedure for the Heavy–Duty manufacturing line.
• Analyzed technician data to recognize modes of improvement and assess solutions to increase performance.
• Performed time studies to distinguish points of improvement in the servicing process.
• Developed a PFMEA for a new product guided by the engineer responsible for the project.
• Assisted in developing a service bulletin for a new product.
Sam’s Club, Freezer/Cooler Associate April 2021 – April 2022
• Managed existing stock and supported the introduction of new products.
• Provided quick customer support to members with professional communication skills.
• Collaborated with other associates to ensure products were readily available for members.
WMU College of Engineering and Applied Sciences, Lab Assistant January – April 2020
• Instructed students on the basics of the drafting process and how to effectively utilize AutoCAD.
• Taught classes once a week, held office hours, and graded assignments and exams while managing a full schedule to ensure success of students in the class.
• Attended frequent team meetings to discuss plans for the next week and how to resolve issues.

EXTRACURRICULARS / AWARDS
• Tau Beta Pi | Active Member Spring 2021 – Present
• Dean’s List Spring 2020 – Present
• Higher Promise Scholar Fall 2019 – Present
• Lee Honors College | Member Fall 2019 – Fall 2021
• Formula SAE | Member Fall 2019 – Spring 2019
• FIRST Robotics Competition | Mechanical/Design Team Lead Fall 2016 – Spring 2019

RELEVANT PROFIENCIES
AutoCAD/Inventor/SOLIDWORKS/CREO Parametric | LabVIEW and MATLAB | Microsoft Office Suite
Problem Solving | Organization/Time Management | Technical Thinking and Application