

## Propulsion Subsystem Thermal Modeling for the FalconSat-5 Microspacecraft

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### Abstract

A high fidelity thermal model was developed to insure that propulsion and payload thermal requirements are maintained during FalconSat-5's useful life and flight operations. The unique propulsion subsystem on-board the microsatellite causes relatively large heat dissipation during its operation, and it has been shown by preliminary thermal analysis to affect the strict thermal requirements of the satellite. Based on a simple 1-D thermal analysis performed by the propulsion subsystem vendor, individual propellant tank heaters were added to the propulsion subsystem design. These individual tank heaters were designed to operate for 10 minutes before thruster firing. Further inspection of the newly designed propulsion subsystem showed that the power consumption of the propellant tank heaters would require a large power source, which would ultimately dissipate a relatively large amount of heat during the propulsion subsystem's operations. The high fidelity thermal model created in this study was used to determine if thermal requirements would be maintained during flight operations of the FalconSat-5 microsatellite. Thermal Desktop® was used to create the thermal model and fidelity was gained by accurately accounting for real material properties, surface optical properties, component thermal masses and detailed heat loads. A parametric analysis was conducted, which included the heat dissipated as a result of the individual tank heater's operation and the 10 minute Hall-effect thruster's operation. The parametric analysis was used to find any thermal issues and suggest revisions to flight operations to solve these issues. WISPERS, iMESA and the array of battery cells all remained within their thermal requirements during the analysis. From the high fidelity thermal model it was determined that operating the individual tank heaters for 10 minutes would cause the maximum temperature requirements of the propellants to be exceeded. This would cause the internal pressures to exceed the requirements of the valves, resulting in valve failure and mission loss. Correct operating times for each heater were found and suggested such that the revised flight operations would insure all thermal requirements were maintained during flight.

### Nomenclature

$A_1$	= area normal to heat transfer
$A_2$	= surface area
$\Delta T$	= temperature difference across layer
$\Delta x$	= thickness of layer
$\varepsilon$	= emissivity
$k_t$	= thermal conductivity

- $\dot{Q}_{cond}$  = rate of heat transfer due to conduction  
 $\dot{Q}_{rad}$  = rate of heat transfer due to radiation  
 $\sigma$  = Stefan-Boltzman constant  
 $T_s^4$  = absolute temperature of the body  
 $T_{surr}^4$  = absolute temperature of the surroundings

## Introduction

FALCONSAT-5 is a 180 kg microsatellite designed by consecutive senior cadet classes at the United States Air Force Academy. FalconSat-5 is constructed as a rectangular box having dimensions of approximately 0.7 meters by 0.64 meters by 0.54 meters. The advantages of this class of satellite are the reduction in cost and the ability to have the satellite serve as a secondary payload on a launch vehicle<sup>1</sup>. FalconSat-5 can be classified as a microsatellite; however there are many unique features that are implemented into this satellite's design and its flight operations that set it apart from many other satellites in this category. Three unique payloads on board FalconSat-5 are iMESA, WISPERS and the propulsion subsystem which includes a 500 Watt Hall-effect thruster and an ammonia cold gas thruster. The WISPERS and iMESA payloads are plasma sensors that will investigate the ambient plasma environment and perturbations to the environment. WISPERS and iMESA will read the perturbations caused by a Hall-effect thruster and an ammonia cold gas thruster.

The unique features of the propulsion subsystem are the 500 Watt Hall-effect thruster, an ammonia cold gas thruster, an array of battery cells capable of discharging up to 1100 Watts of power that powers the propulsion system, and three independent propellant tank heaters designed to maintain the critical temperatures for the liquid and gaseous ammonia and xenon propellants. The need for three individual tank heaters was a result of a simple analysis, performed by the propulsion subsystem vendor, on a 1-D thermal model of the propulsion subsystem that indicated the propellants would not meet their minimum temperature requirements needed for the Hall-effect thruster's operation. Further inspection of the propulsion subsystem, after the implementation of the individual tank heaters into the design, showed that the increased power needed to operate the individual propellant tanks would cause a relatively large amount of heat dissipation within the satellite during flight operations. As a result of the relatively large propulsion subsystem, its complex nature, and the simple preliminary analyses, a high fidelity 3-D thermal model was deemed necessary to insure the thermal requirements of all flight hardware were maintained during the flight operations of the FalconSat-5 microsatellite.

Although FalconSat-5 is a small satellite, the components on board have a thermal impact on the propulsion subsystem; the Hall-effect thruster and the propulsion subsystem, due to their complex configurations and thermal requirements, have a relatively large thermal effect on the FalconSat-5 microsatellite. Simple preliminary analyses showed that the heat that can be dissipated at any given time on orbit, due to the power needed to drive the Hall-effect thruster and the individual tank heaters, can be relatively large and requires careful thermal modeling to insure the thermal requirements of the internal and external components are maintained during flight operations. Due to the relatively large amount of heat dissipated during the operation of the Hall-effect thruster, the complexities of the propulsion subsystem and the strict thermal requirements within FalconSat-5, a high fidelity thermal model is necessary to correctly analyze internal and external heat transfers. The strict thermal requirements of all propulsion subsystem components are extremely

**Table 1. Thermal Requirements of Critical Components.**

Component	Minimum Thermal Requirement (K)	Maximum Thermal Requirement (K)
Xenon Propellant	293	No Maximum Requirement
Liquid Ammonia Propellant	293	323
Gaseous Ammonia Propellant	313	No Maximum Requirement
Battery Box	243	333
WISPERS	208	353
iMESA	218	333

important to the flight operations of FalconSat-5. Due to the impact of the large amount of heat exchange, over an approximate time period of a 10 minute thruster firing time, payloads and components of FalconSat-5 must be closely monitored to insure they are kept within their thermal requirements, as shown in Table 1. Thermal Desktop® allows the temperature profiles of all components to be dynamically analyzed while the satellite is orbiting into and out of eclipse in a circular orbit with an inclination of 72° and an altitude of 650 kilometers.

### Thermal Model: Theory

Thermal Desktop® was used to create and analyze a thermal model of FalconSat-5. Usually these codes are considered “finite difference” when in fact they are geometry-independent solution engines that can be used to solve not only finite difference problems but also finite element problems<sup>3</sup>. Thermal Desktop® works within an AutoCAD® environment that uses finite difference solids, which are built in an AutoCAD® software palette. This solid method of modeling is capable of generating a user controlled mesh of nodes, in all three axes, that allows for a detailed heat transfer analysis. Contactors are then used to allow heat transfer between adjoining solids. This method of connecting solids allows the model to account for the type of material, optical properties and the thickness between the solids. Using the node meshed solids, along with contactors between adjoining solids, correct conduction and radiation is modeled between all components throughout the satellite. Previous satellites modeled at the United States Air Force Academy, such as the FalconSat-2, were thermally analyzed using MatLab and used Simulink to coordinate the programming<sup>4</sup>. Due to the user friendly format and quick model layering, changes to the thermal model using Thermal Desktop® are made quickly, allowing a large array of information to be obtained automatically without the use of a large amount of external code and programming.

Internal and external heat transfer within the high fidelity model will account for all conduction and radiation, shown in Eq. 1 and Eq. 2 respectively, in a space environment; convection in this space environment is assumed negligible<sup>2</sup>. Methods of radiation examined in this environment are solar radiation reflected off the Earth, direct solar radiation, radiation from one surface into the surroundings, as shown in Eq. 2, and Earth infrared radiation throughout the orbit. Parametric analyses conducted with the high fidelity thermal model are used insure that all components and payloads will operate within their temperature requirements.

$$\dot{Q}_{cond} = k_t A_1 \frac{\Delta T}{\Delta x} \quad (1)$$

$$\dot{Q}_{rad} = \varepsilon \sigma A (T_s^4 - T_{surr}^4) \quad (2)$$

### Thermal Model of FalconSat-5

The thermal model of FalconSat-5 has a relatively high level of fidelity representing all internal components, as shown in Fig. 1. External components, solar arrays and payloads are accurately modeled to increase the level of fidelity, as shown in Fig. 2. Components are modeled to scale in three dimensions. Once a component is modeled on the satellite, the correct thermal mass, optical properties, thermophysical properties and real material properties are input into the model to insure correct heat transfer paths. Through careful piece by piece construction and analysis, the thermal model accurately reflects FalconSat-5 with representative spacecraft materials and the correct overall spacecraft mass. This method of modeling allows heat transfer to be viewed dynamically as it would occur on orbit during any flight operational configuration.

To increase the level of fidelity in the model, heat loads are applied to the finite difference solids representing the propulsion subsystem and individual propellant tank heaters. This allows the complex heat transfer during the operations of the Hall-effect thruster, and the impact of this relatively large amount of heat dissipation to other payloads and components, to be correctly analyzed. The heat loads account for the 62 Watts of heat dissipation inside the battery box, the 65.2 Watts of heat transfer inside the power processing unit (PPU) box, the 200 Watt tank heater applied to the xenon propellant tank, the 200 Watt heater applied to the liquid ammonia propellant tank and the 100 Watt heater applied to the gaseous ammonia propellant tank. All components to which heat loads are applied are shown in Fig. 1. The heat dissipation values from the battery box were determined by assuming that 10% of the difference of the power being drawn from the battery and the power coming into the battery from the solar panels is dissipated as heat. Heat dissipation within the PPU box had been previously determined from the preliminary, simple analyses of the 1-D thermal model.

The intricacies of the propulsion subsystem require all heat loads to be analyzed in a transient setting, during the parametric analyses, where the heat dissipation is only happening for the amount of time corresponding to the thruster firing. For example, when the Hall-effect thruster is operating, the array of battery cells powering the thruster dissipates heat for a total of 10 minutes. Prior to the thruster firing, the propellant tank heaters, initially from preliminary, simple analyses, needed to run for 10 minutes to maintain the appropriate temperature ranges of the propellants throughout the thruster's operations. This transient heat transfer requires a large parametric analysis to be conducted such that any thermal problems within the model can be found such that recommendations can be suggested to flight operations before the FalconSat-5 microsatellite is in orbit. When a thermal requirement is broken, the high fidelity thermal model is used to find these potential problems and suggest changes to flight hardware and operations to insure safety of all components.

To insure the thermal requirements, shown in Table 1, of all internal and external components are met throughout the life of FalconSat-5, a parametric, thermal analysis that accounts for the relatively large

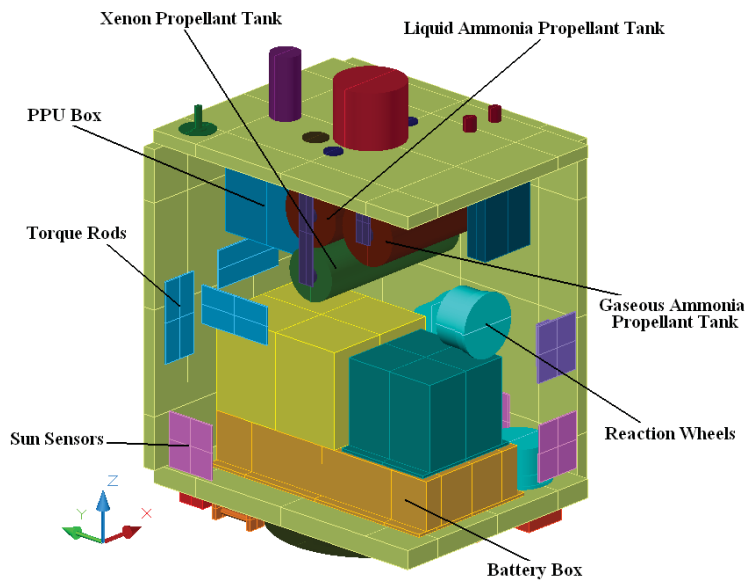


Figure 1. Internal Fidelity and Internal Component Diagram.

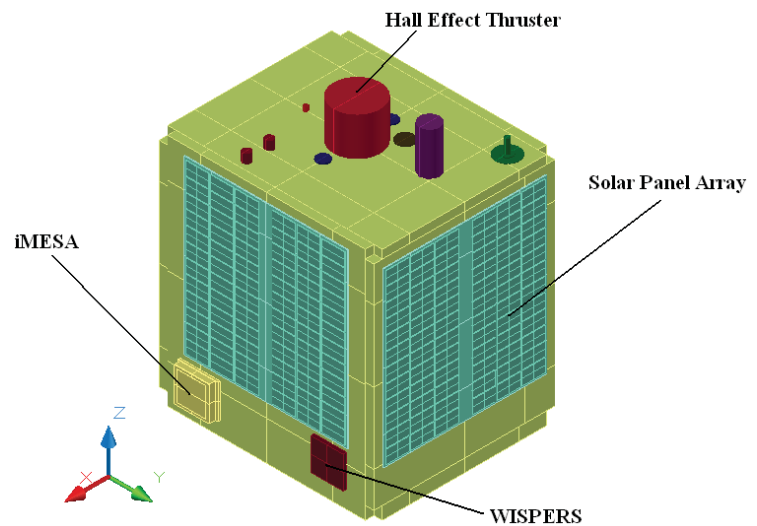


Figure 2. External Fidelity and Internal component Diagram.

heat dissipation created during the operation of the Hall-effect thruster is conducted. While the model is in a simulated orbit, prewritten commands are executed at certain times to account for the internal heat dissipation, occurring on the applied heat loads, for flight operations of the thruster and the individual propellant tank heaters. Thermal Desktop® also evaluates the external heating environment FalconSat-5 will encounter due to heat exchange from solar radiation reflected off the Earth, direct solar radiation, radiation from one surface into the surroundings and Earth infrared radiation throughout the orbit.

## Results

Using the preliminary design and operation times, acquired from the propulsion subsystem vendor's preliminary 1-D thermal model analyses, and the high fidelity thermal model, a preliminary analysis on the FalconSat-5 microsatellite was conducted. This preliminary analysis was simulated to indicate the initial thermal state of the microsatellite. From the results of this analysis and the thermal requirements of the payloads and components, as shown in Table 1, conclusions could be drawn as to whether or not the propulsion subsystem would create a thermal issue. After running the analysis, it was found that the three individual tank heaters, operating for 10 minutes, would cause the temperature of the liquid ammonia propellant to exceed its maximum thermal requirement of 323K. The red line, shown in Fig. 3, is the maximum thermal requirement of the liquid ammonia propellant. The liquid ammonia propellant would reach a temperature of approximately 820K, as shown in Fig. 3, if the 200 Watt heater attached to the tank was allowed to operate for 10 minutes. Exceeding this thermal requirement would cause the valves to fail. Therefore revisions to the flight operations of the FalconSat-5 microsatellite were necessary to solve this problem.

With the high fidelity thermal model representing the true FalconSat-5 and its flight operations, a full parametric analysis has been conducted to view the temperature profiles of the important components, payloads and the relatively large propulsion subsystem during the operation of the Hall-effect thruster. A critical experimental package on-board FalconSat-5 includes the Hall-effect and cold gas propulsion systems. From a thermal standpoint, this experimental package has the highest potential to affect the thermal range of the other payloads and subsystems and has critical temperature requirements of its own. For example, prior to the operation of the propulsion systems, the liquid ammonia tank must be within the

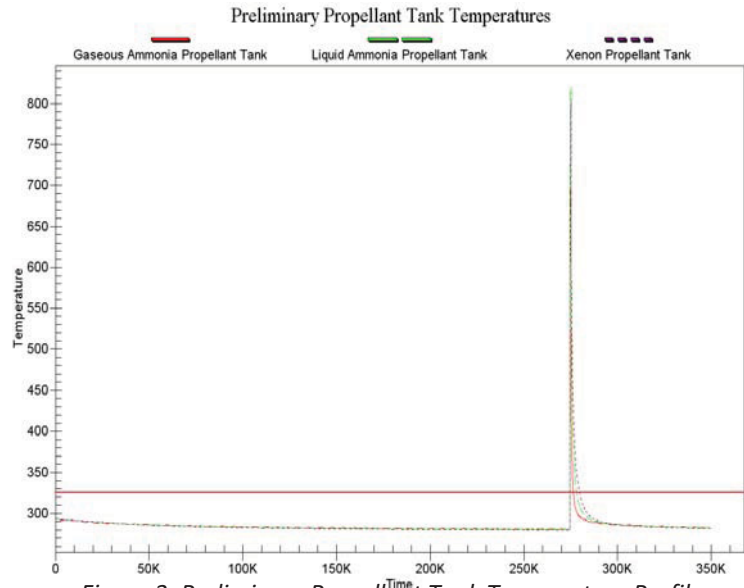


Figure 3. Preliminary Propellant Tank Temperature Profiles.

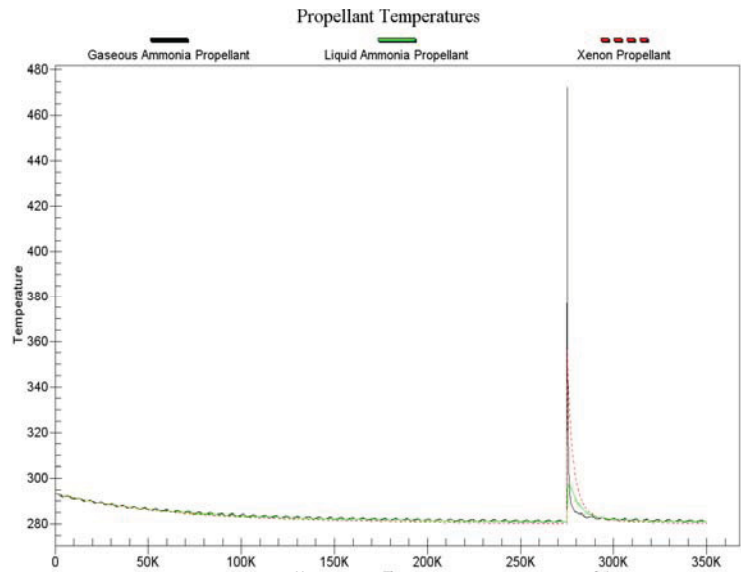


Figure 4. Propellant Tank Temperature Profiles.

temperature range between 293K and 323K, the gaseous ammonia tank must be heated to a temperature greater than 313K, and the xenon tank must be maintained at a temperature greater than 293K. These temperatures insure the fluid properties within the tank remain constant during operation while also insuring the pressure limits of the valves are not exceeded. Individual heaters on each tank were previously sized based on a simple, preliminary analysis to maintain the thermal requirements of the tank propellants. Values from the preliminary analysis were used as base line conditions for the thermal model. After the operations of the individual tank heaters are conducted, the Hall-effect thruster operated for 10 minutes. This operation causes the array of battery cells and the PPU box to dissipate additional heat, which must be monitored to insure the thermal requirements of all FalconSat-5 components.

The new, high fidelity thermal model described in this paper found that the individual propellant tank heaters' preliminary flight configuration would cause the liquid ammonia propellant to exceed the maximum thermal requirement, as shown in Fig 3. Due to the fact that the individual propellant tank heaters are resistance heaters, the operational time of the heaters was the variable in the parametric analysis. This thermal requirement was explored, by parametric analysis, and has been used to improve the heater design and offer operational data to suggest when the heaters will need to operate and for how long. The higher fidelity model suggests that the 100 Watt heater on the gaseous ammonia propellant tank would only need to be operated for 55 seconds, the 200 Watt heater on the liquid ammonia propellant tank would only need to be operated for 5 seconds and the 200 Watt heater on the xenon propellant tank would only need to be operated for 55

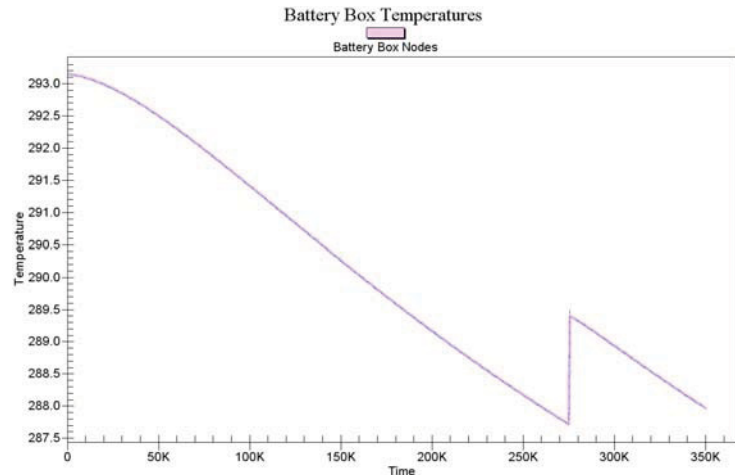


Figure 5. Battery Box Temperature Profile

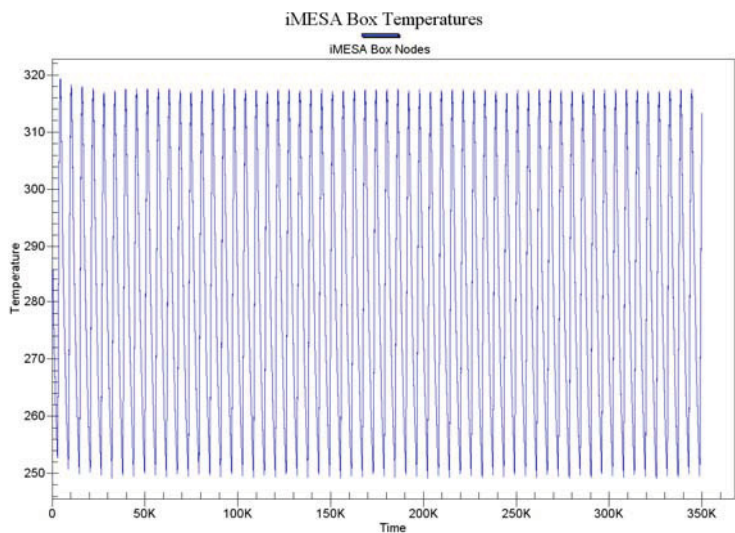


Figure 6. iMESA Temperature Profile.

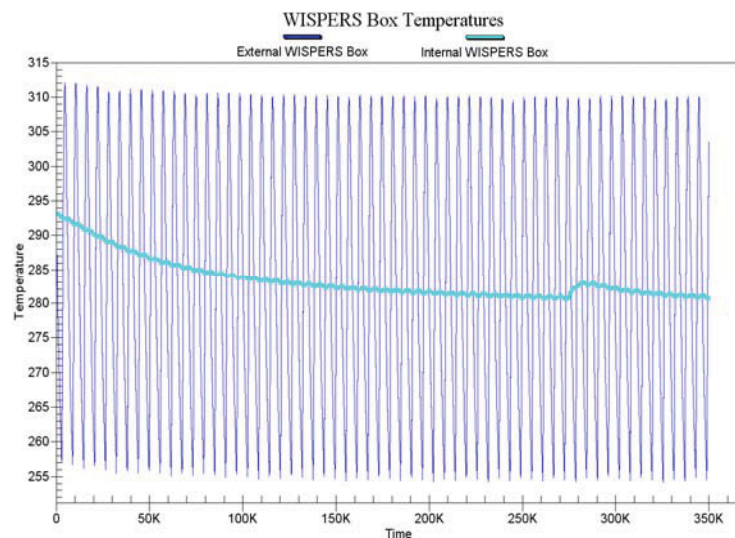


Figure 7. WISPERS Temperature Profile.

seconds. Figure 4 shows that using these time frames for the individual propellant tank heaters, the thermal requirements of the propellants are maintained. This analysis has been critical for the microsatellite's operational scenario since it has identified a major source of power savings for the spacecraft. Reducing the power consumption of the individual propellant tank heaters by approximately 8-% is suggested with the high fidelity thermal model.

The new thermal model has also shown that the other experiments, payloads, and subsystems can be maintained within their thermal requirements for all operational scenarios investigated, including the optimized flight operation of the individual propellant tanks. The array of battery cells' thermal requirements, greater than 243K and less than 313K, are met, as shown by the temperature profile in Fig. 5. The iMESA payload meets all thermal requirements, greater than 218K and less than 333K, as shown in Fig. 6. The WISPERS payload meets all thermal requirements, greater than 208K and less than 353K, as shown in Fig. 7. The sinusoidal oscillations of the temperature profiles, of iMESA and WISPERS payloads, are caused by FalconSat-5 traveling into and out of eclipse during the simulation.

### **Conclusion**

Conducting a parametric analysis using a high fidelity thermal model of the complete FalconSat-5 microsatellite was necessary due to the unique propulsion subsystem and how the operations of the Hall-effect thruster thermally impacts the other components and payloads. The high level of fidelity in the FalconSat-5 model, developed as a result of the operation of the Hall-effect thruster and the unique features comprising the propulsion subsystem of the FalconSat-5 microsatellite, which the model analyzes, sets this thermal model apart from other projects of this magnitude. Without this high fidelity model and parametric analyses, initial 1-D thermal models would have underestimated the relatively large amounts of heat dissipation within the FalconSat-5 microsatellite. Revisions to flight operations, regarding the operating times of the individual propellant tank heaters, have been suggested as a result of this high fidelity thermal model to solve the thermal problems encountered within the initial parametric analysis of the FalconSat-5 microsatellite.

It was initially suggested, from preliminary 1-D thermal analyses conducted by the vendor of the propulsion subsystem, that the individual propellant tank heaters would need to operate for a total of 10 minutes before firing the thruster. Using the high fidelity thermal model, it was shown that operating the individual propellant tank heaters for 10 minutes would cause the maximum thermal requirement of the liquid ammonia propellant, 323K, to be exceeded. The temperature acquired by the liquid ammonia propellant during this analysis was approximately 820K. This violation of the thermal requirement was a problem because the pressure inside the tank would be too large for the valves to maintain if the liquid ammonia propellant exceeded its thermal requirement during flight operations. This excess pressure would therefore cause failure and mission loss. It was then determined that parametric analyses of the individual propellant tanks' operating times were necessary to solve this thermal issue.

The high fidelity thermal model of the entire FalconSat-5 microsatellite was essential due to the thermal interactions between the unique propulsion subsystem and the FalconSat-5 microsatellite, and vice versa. The thermal model has successfully been used to suggest revisions to flight operational profiles to insure all thermal requirements are met during the flight operations of the FalconSat-5 microsatellite. The higher fidelity model suggests that the 100 Watt heater on the gaseous ammonia propellant tank would only need to be operated for 55 seconds, the 200 Watt heater on the liquid ammonia propellant tank would only need to be operated for 5 seconds and the 200 Watt heater on the xenon propellant tank would only need to be operated for 55 seconds. These time frames will insure that all components and payloads remain within their thermal requirements during the operation of the propulsion subsystem.

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