State-of-the-Art Thermal Analysis Methods and Validation for Small Spacecraft

Ae241 Literature Survey

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Introduction

A detailed and accurate thermal analysis is critical to the success of any spacecraft mission and is thus an integral part of the development cycle. Without an adequate thermal control system, the often extreme temperature ranges and gradients endured by spacecraft in flight may cause component temperatures to exceed operating or survivability limits, leading to decreased performance or even permanent damage. Conversely, NASA's Guidelines for Thermal Analysis of Spacecraft Hardware (Guidelines from here forward) caution that an overly conservative control system may result in excessive power and weight, which drive the cost of the mission [1]. The Guidelines summarize the benefits of proper and iterative thermal analysis: not only will the analysis provide thermal loads and load histories, but can also pinpoint design flaws in the early stages of development, allow for thermal design optimization, and provide a basis for evaluating thermal performance in flight.

Small spacecraft like CubeSats have now demonstrated success in driving university-based and other small-scale missions. While such spacecraft are heralded for their short development times and relative simplicity, their thermal control systems can be much harder to design than their larger counterparts. Smaller surface area translates to less room for heaters and less room for solar panels to power those heaters or any other resource-intensive thermal controller. The following paper provides an overview of the current state-of-the-art in thermal analysis, with emphasis on small spacecraft. Such topics covered include environmental considerations, thermal control methods, and testing procedures. The paper summarizes the important points outlined by NASA's Guidelines, as well as those from a presentation given by Robert N. Miyake of Jet Propulsion Laboratory [4]. It also draws from two specific examples of thermal analysis performed on small spacecraft. The first is the Formation Autonomy Spacecraft with Thrust Relative Navigation, Attitude, and Crosslink (FASTRAC) [3]. FASTRAC consists of twin satellites in Low-Earth Orbit developed by University of Texas-Austin. The second is NASA Ames's PharmaSat, a 3U cubesat-sized nanosatellite with a biological experiment payload located inside a pressure chamber [2]. This paper will cover how these teams chose to perform thermal analysis and testing, as well as their results and control methods.

Heat Source Considerations

The first step in thermal analysis is to identify the sources of heat incident upon the spacecraft. Solar heating is relevant to any space mission. For orbiting spacecraft, infrared radiation and solar reflection from the nearby body is also important. A detailed thermal analysis must also include heat dissipated by the electrical components of the spacecraft. For large-scale missions, JPL also suggests accounting for the universal thermal background (2-3K), which can be significant for cryogenic flight elements since it limits thermal rejection to space.

FASTRAC and PharmaSat both operate in low-Earth orbit. Thus, thermal analyses performed on these spacecraft focused on solar heating, infrared radiation from Earth, Earth albedo (solar reflection) heating, and internal heat. The magnitudes of heat fluxes from the first three sources are highly dependent on the exact orbital parameters and orientation of the spacecraft. The orbit determines not only the distance between the spacecraft and the heat source, but how much time the spacecraft

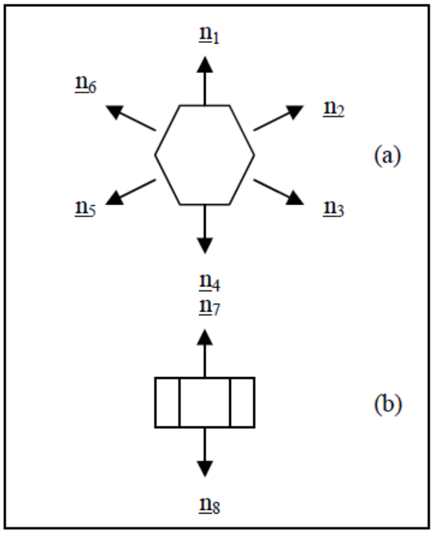

Figure 1: FASTRAC surface normals

spends shadowed from the Sun by the Earth, which is the origin of the most transience in thermal loads. The orbit of PharmaSat was known to be $40.5°$ inclination at $460\,\mathrm{km}$ at the time of thermal analysis, and thus the thermal model had exact values of shadow time and sun time. Conversely, FASTRAC did not have a launch vehicle chosen and thus the team analyzed a number of possible orbits at different times of year and computed the corresponding minutes of shadow for each. A worst case hot scenario was then established, using the tested orbit that had minimum shadow time, $300\,\mathrm{km}$, $57°$. Similarly, an orbit with $28.5°$ inclination at $300\,\mathrm{km}$ established the worst case cold scenario, with maximum shadow time.

The orientation of the spacecraft with respect to the Sun and Earth also affects the magnitude of the heat flux, as it changes the view factor and total surface area exposed to radiation. A single FASTRAC satellite is a hexagonal prism, and thus has eight surface normals, as shown in Figure 1. Each of these orientations was tested in the thermal analysis. PharmaSat had magnetic rods that fixed the orientation of the spacecraft with respect to Earth's magnetic field. Thus the attitude at any point in the orbit could be modeled with an equation dependent on the true anomaly:

$$\omega_n = A_n + B_n \cos(f) + C_n \sin(f)$$

Miyake cautions that, in establishing worst-case scenarios, all possible variables should be considered. He provides the example of the cold case, stating that it should include:

1. An orbit that minimizes sun time
2. An orientation that minimizes absorbed sunlight
3. A minimum estimate of internal power dissipation
4. Minimum values selected for Earth albedo and solar constant, which are then reflected in estimate of Earth blackbody temperature
5. Minimum absorptivity and maximum emissivity of thermal coatings
6. MLI blanket effective emissivity or conductance for coldest condition

Operating Temperature Ranges

In order to focus the thermal analysis, the critical components and subsystems of the spacecraft should be established. These components have the smallest survival temperature range, and thus bound the thermal requirements of the spacecraft. Both FASTRAC and PharmaSat identified the battery as the most thermally sensitive element; FASTRAC stated operating temperature limits of 5°C and 45°C, while PharmaSat adjusted the lower bound to 0°C. FASTRAC also acknowledged the communication system and avionics system as secondary critical subsystems, with ranges from 5°C to 65°C. All other components on the PharmaSat bus structure were industrial grade electronics, surviving temperatures from $-40°C$ to $85°C$. However, the payload itself had separate temperature requirements determined by the science experiment. These requirements varied for different points in the mission, and are summarized in Figure 2.

Mission Phase	Fluidics Card (FC) Requirement	Fluidics Reservoir (FR) Requirement
Active Phase temperature	Set-point of (22°C - 30°C) +/-0.5°C	>20°C +/-3°C and < 2°C + Set-point
Standby Phase temperature	4 - 30°C	4 - 30°C

Figure 2: PharmaSat payload temperature requirements. The active phase refers to the duration over which the experiment is performed. The standby phase refers to when the experiment is in storage.

Level of Analysis

Both the presentation by Miyake and NASA's Guidelines recommend performing an updated thermal analysis at every stage of spacecraft development, with the level of detail increasing as launch approaches. Specifically, Miyake suggests performing a quick hand-calculation at the beginning of the mission to obtain an estimate of the bulk temperature of the spacecraft. For this calculation, the spacecraft can be treated as a sphere with uniform optical properties representative of the spacecraft average. Heat sources can be limited to solar flux as determined by the spacecraft's range from the Sun and internal power dissipation.

In general, thermal analysis must be performed using finite element or finite difference methods implemented by computer software programs. These programs reduce the spacecraft to a mesh of nodes and compute the heat transfer between these nodes. External heat sources act as boundary conditions for nodes on the spacecraft surface, and heat is propagated throughout the mesh. Temperature and heat flux values are obtained at each node, and thus finer meshes enable greater accuracy in representing the thermal distribution.

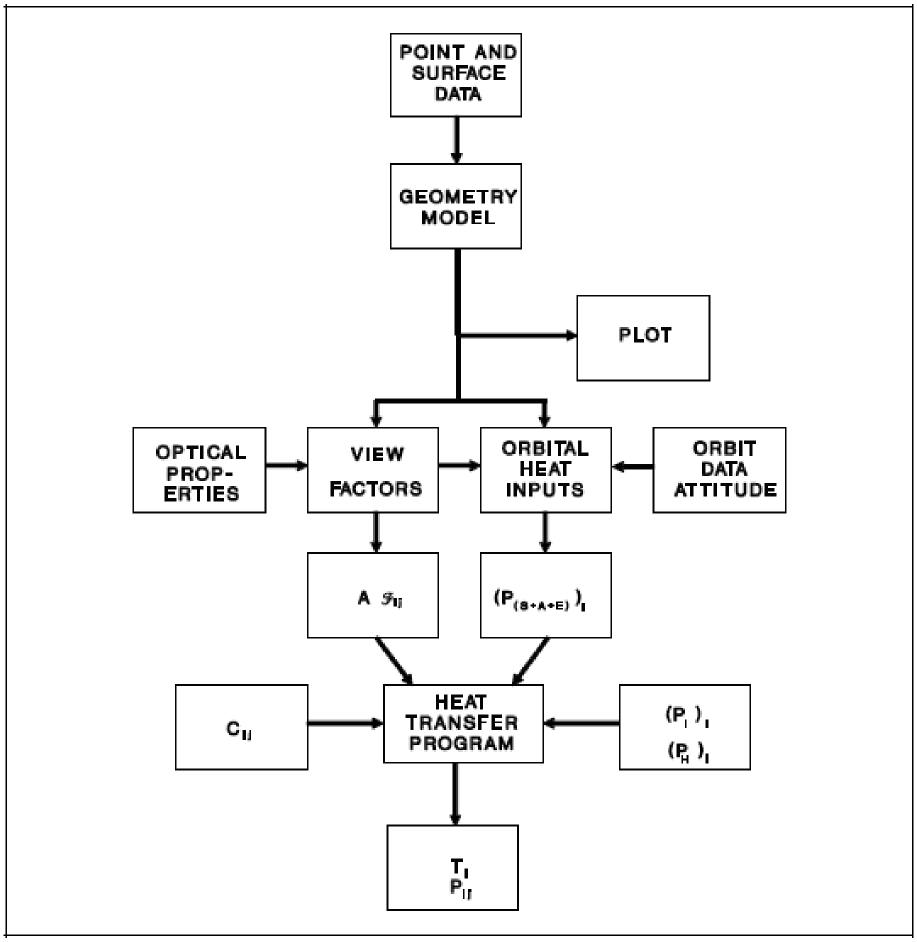

Figure 3: Flow chart detailing the critical steps in performing thermal analyses on spacecraft. $\mathcal{F}$ = radiation coefficient. A = surface area. P_E = absorbed Earth IR radiation. P_S = absorbed sunlight. P_A = absorbed Earth albedo. P_I = component power. P_H = heater power. C = thermal conductance. T = temperature (absolute). i, j = node number, including space.

NASA's Guidelines provides a chart, shown in Figure 3, which outlines the steps needed in order to create and analyze a thermal model. The process begins with generating a geometric representation of the spacecraft with a computer-aided design (CAD) program. This model can be as detailed or as simplified as required by the level of analysis. Greater detail should be applied to critical subsystems or components; NASA's Guidelines propose isolating these critical components and generating a more accurate model if necessary. Figure 4 and Figure 5 show the geometry models for FASTRAC and PharmaSat respectively. PharmaSat was modeled in full. However, in order to save computation time and focus the analysis on critical subsystems as suggested by NASA's Guidelines, the FASTRAC model only included 1/3 of the spacecraft. This section contained the battery, the voltage regulator (a primary source of heat dissipation), and part of the fuel tank.

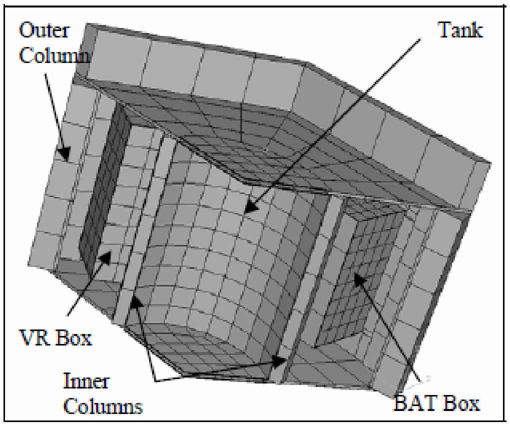

Figure 5: FASTRAC thermal model. Only 1/3 of the spacecraft was simulated.

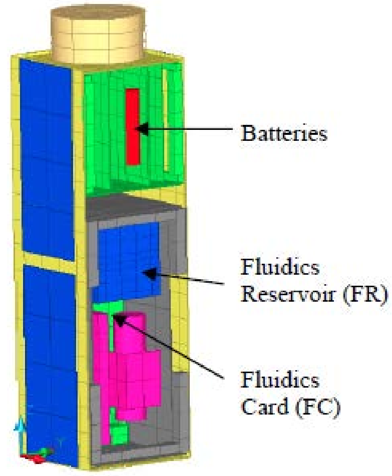

Figure 5: PharmaSat thermal model

Once the geometry model is obtained, optical properties must be applied to each surface and material properties to each volume section. Then orbit and attitude data is used to determine the transient external heat fluxes applied to the spacecraft. A heat transfer program then subjects the model to these boundary conditions and propagates heat transfer throughout the spacecraft. The result is a set of temperatures and heat fluxes at each node. There are many different software packages available, and cost, availability, and accuracy should be considered in choosing one best suited for a specific mission. NASA's Guidelines suggest SINDA (Systems Improved Numerical Difference Analyzer). SINDA alone is just a finite difference analysis package, and thus the external heat sources must be computed using another method. The FASTRAC team computed the environment heat fluxes using Matlab, and then applied these fluxes to a model in Abaqus, another finite different analyzer. Miyake proposes the use of Thermal Desktop, which is an integrated spacecraft thermal analysis package. Integrated packages have the ability to compute environmental heat fluxes given orbital parameters and attitude data. The PharmaSat team used Thermal Desktop for their analysis.

Thermal Control Methods

Thermal analysis is an iterative procedure. It should be performed in the initial stages of development in order to aid in the design and assess the adequacy of the thermal control system. If any of the components endure temperatures outside of the operational or survivability ranges, the thermal control system should be adjusted accordingly and the thermal analysis repeated.

Miyake divides thermal control methods into two main categories: passive and active. Passive systems are defined as any system that, after installation, requires no further resources from the spacecraft. These systems tend to be simple, reliable, and have lower cost and risk. Common passive controls include: multi-layer insulation (MLI), thermal coating, thermal storage through phase change materials, thermal transfer (heat pipes), and radiation blockers (sun shades). MLI is widely used on spacecraft to reduce temperature swings and heat loss. It consists of a series of gold or aluminum-plated layers separated by vacuum. The effect of each sheet thermally radiating back to its neighboring sheet reduces radiative heat loss, and thus the effective emissivity of MLI is very low (.002 to .05, depending on the number of layers). Passive control can also be achieved by regulating conductance throughout the system; components can be isolated by surrounding them with a low conductance material or heat transfer increased through a high conductance material.

Active systems require power, sensors, and data control from the spacecraft. However, they can be much more effective and precise than passive systems. Active control methods include coolers, heaters, active heat pipes or pumps, thermal switches, and dewars.

Small satellites often do not have surface area for radiators, which release heat for hot environments, or solar panels, which power heaters for cold environments. Thus passive thermal designs are typically required. FASTRAC is mostly composed of 6061 T-6 aluminum and covered with Kapton MLI thermal blankets. The blankets reduce temperature swings by trapping heat, but may actually cause overheating. Thus they were designed with open areas that act as radiators. PharmaSat also employs MLI. The team computed the effective emissivity of MLI using the following equations:

$$\varepsilon_{eff} = \left(0.000136\frac{1}{4\sigma T_m^2} + 0.000121T_m^{0.667}\right) f_N f_A f_p$$

$$f_A = \frac{1}{10^{(0.372 logA)}}$$

where A is the surface area, T_m is the mean temperature, f_N is a function of the number of layers, and f_p is a function of the number of seams. PharmaSat is also equipped with heaters designed to maintain $27°C$ in the biology experiment using software control and sensors. Specialized coatings and materials also helped to regulate the temperatures of vital subsystems. For instance, a trade study was performed which determined that gold plating over aluminum surfaces would yield the best heat retention, since $\frac{\alpha}{\varepsilon} \approx 10$. The payload enclosure surfaces were treated with this coating. Furthermore, low conductivity materials (Ultem and Delrin), isolated the payload biological components from the rest of the spacecraft. Titanium bolts and Ultem washers reduced the thermal path to the payload pressurized chamber from solar panels.

Thermal Testing

Computational thermal analysis should not be assumed accurate without proper validation from physical thermal tests. NASA's Guidelines recommend performing quick calculations or analyzing simplified thermal models before the testing phase, in order to validate that the test hardware can provide necessary temperature extremes and to predict transition times between hot and cold soaks. The Guidelines also note that test environments often cannot match orbital environments. No matter what the testing conditions are, the same conditions should be implemented in the thermal model and the results compared. Thus any discrepancies can be included in further analyses and the temperature distribution of the thermal model when subject to the true environmental condition can be taken as accurate.

FASTRAC was subject to thermal cycling in a vacuum chamber. During a 90-minute orbit, it was estimated that 30 minutes were spent in shadow and 60 in full sun. The thermal cycle followed this pattern. The hot case was modeled with infrared lamps placed as shown in Figure 6. The lamps on the outside of the craft are 1600 W and those on the faces are 1000 W. The cold case was simulated with liquid nitrogen. Solar panels were not ready before testing time, so the spacecraft was covered in black-painted glass, which was tested to have similar optical properties to fused silica and ceria-doped microsheet. The vacuum chamber was reduced to a pressure of about 10^{-5} torr. During the test, the spacecraft components were equipped with temperature sensors and performed normal flight operations. Functional checks were performed before cycling began and after each hot and cold soak.

PharmaSat was subject to thermal vacuum tests and thermal imaging tests. Thermal imaging was used to pinpoint hotspots in the system, in order to design better thermal control near those spots.

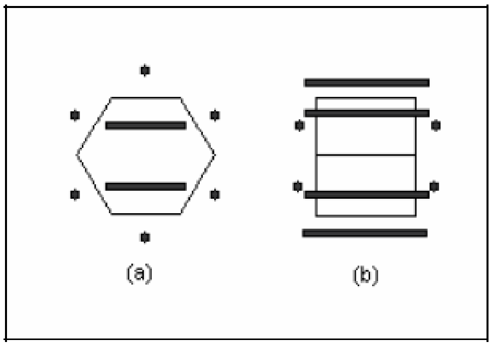

Figure 6: Placement of infrared lamps during thermal vacuum tests of FASTRAC

Analysis Results

PharmaSat

Again, the orbit of PharmaSat was known to be 40.5° at 460 km at the time of analysis, and thus hot cases and cold cases were established based on choosing the appropriate extremes for average solar flux, albedo factor, Earth IR flux, and beta angle, which establishes the percentage of shadow time and is dependent on the time of year.

	Q_{sun} [W/m^2]	Albedo Factor	Q_{IR} [W/m^2]	Beta Angle
Hot Case	1414	0.26	257	63
Cold Case	1322	0.19	218	0

Figure 7: Heat flux parameters for hot and cold cases of PharmaSat.

Thermal Desktop was used to implement these values in the thermal model. Figure 8 shows the resulting variations in average surface temperature as the spacecraft traverses its orbit.

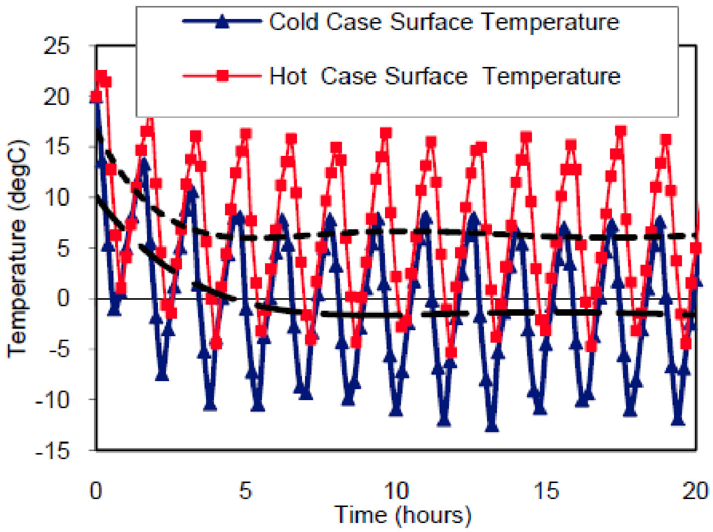

Figure 8: Thermal model analysis results for orbital environment fluxes.

The plot shows how the spacecraft reaches thermal equilibrium about 4.5 hours (three orbital periods) after being inserted into the orbit. The average equilibrium surface temperature was found to be 6.5°C in the hot case and −1.5°C in the cold case. Thermal vacuum and power management (TVPM) test temperatures were established by adding a ±5°C margin to the predicted average temperatures, as demonstrated in Figure 9.

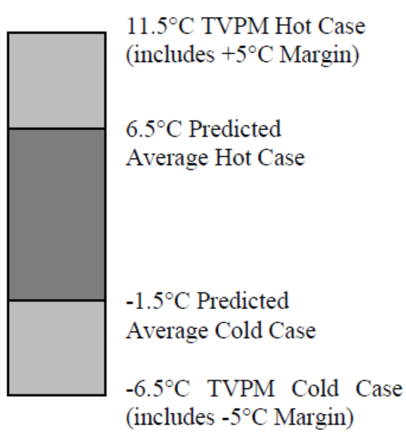

Figure 9: PharmaSat predicted temperature ranges and test temperature ranges.

Figure 10 shows how the average temperature of the solar panels during the cold test compared to the model predictions. The test temperature was about one degree Celsius warmer than the model temperature. This discrepancy was included in subsequent analyses of the thermal model.

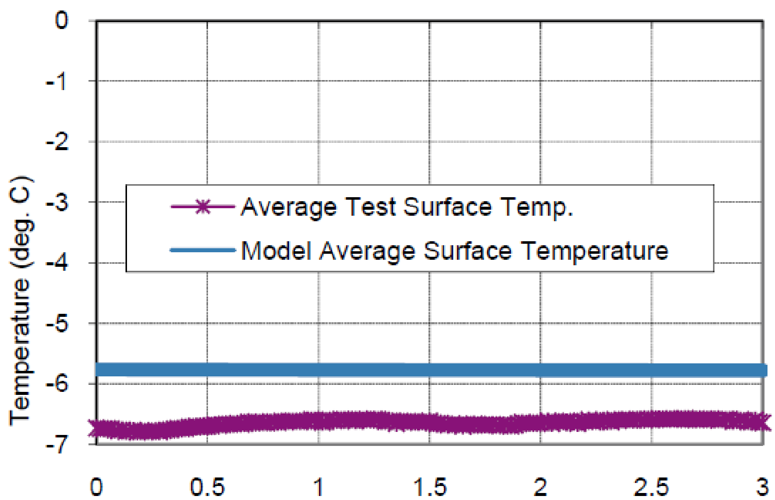

Figure 10: PharamSat comparison of average temperature of solar panels as computed by the thermal model and as measured from the vacuum test.

FASTRAC

The expected temperature range was computed by approximating the satellite as a spherical body and subjecting it to the worst case hot and cold orbits previously mentioned. This range was found to be $-71°\text{C}$ to $51°\text{C}$, a differential of $122°\text{C}$, which the team stated is similar to a typical value for satellites of $125°\text{C}$. The team then established an acceptance temperature range by adding a margin $\pm 5°C$ to account for workmanship errors. The qualification range added another $\pm 5°C$ for weaknesses in the thermal design. These ranges are summarized by Figure 11. The limiting subsystem temperature range is bounded by the avionics and communications systems, not the battery system, since the battery was not operational during testing.

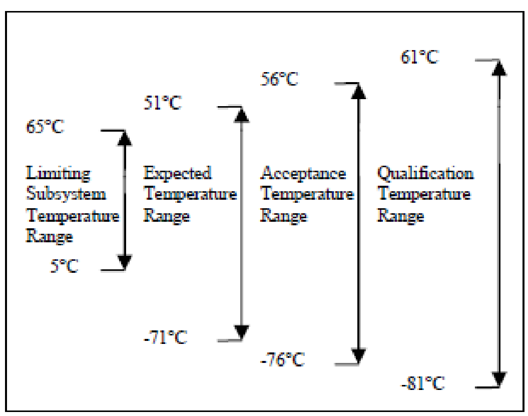

Figure 11: Various temperature ranges as computed by the thermal model of FASTRAC.

Thermal vacuum testing, with the cycle bounds as previously described, yielded a transient average battery temperature as shown in Figure 12.

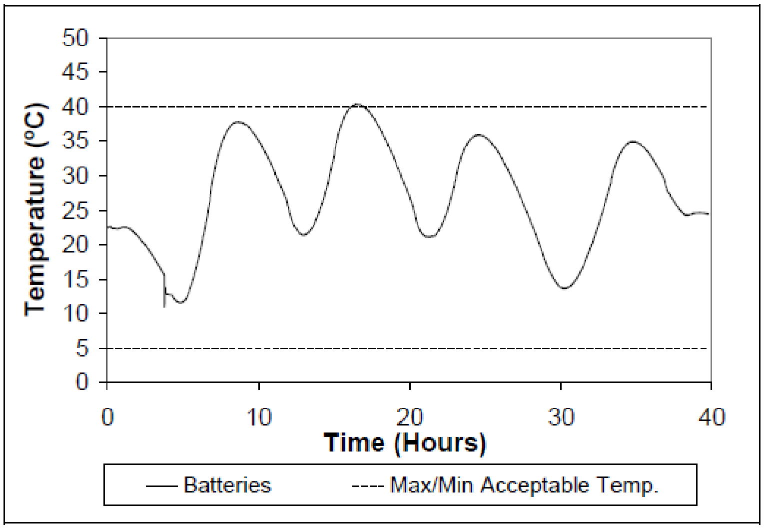

Figure 12: FASTRAC battery temperature during thermal testing.

Figure 13 compares the results of the test with the temperatures predicted by subjecting the thermal model to the same conditions. The team cited the simplification of the model relative to the real spacecraft as the source of the ~10°C discrepancy, which was then added to the predicted temperature for subsequent thermal analyses.

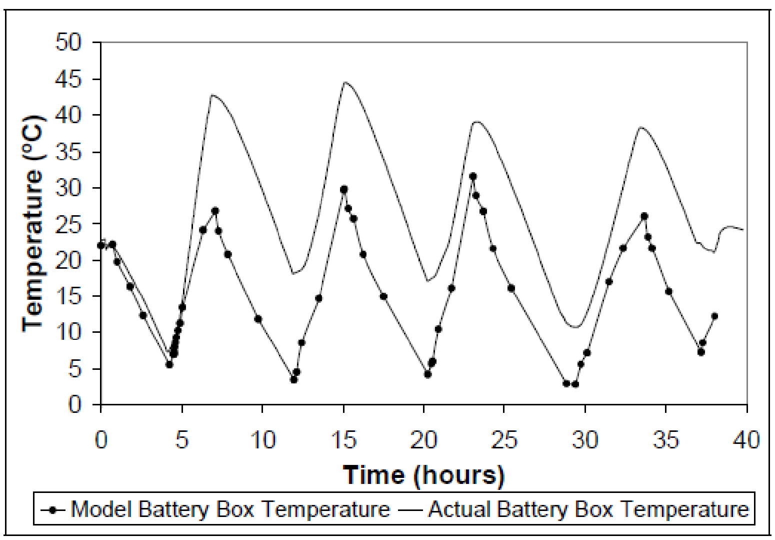

Figure 13: Comparison of FASTRAC battery temperature as measured by the test and as predicted by the model.

The thermal model was then subject to environmental fluxes for the hot case orbit and cold case orbit over the course of 18 periods and starting at a temperature of 25°C. The results showed that, with the 10°C increase based on test results, the battery temperature exceeded operational ranges in the hot case.

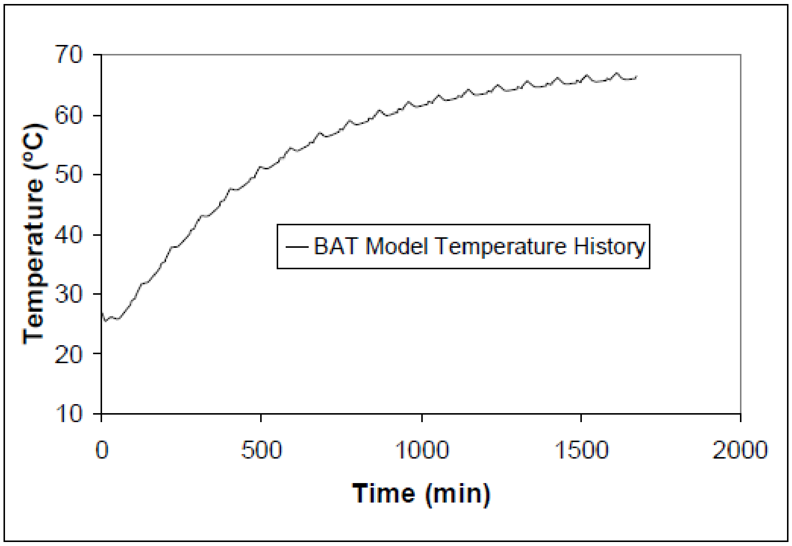

Figure 14: Simulation of battery temperature subject to orbital conditions.

The team attempted to lower the battery temperature by adding a 10 revolution/orbit rotation to the spacecraft, which was the maximum amount of rotation allowed by the GPS signal. However, the battery still endured temperatures outside the operational range. It was thus determined that an orbit with at least 39% shadow time was required to maintain allowable temperature limits, which can be achieved with a maximum orbit altitude of 360 km.

Conclusions and Applications

Detailed and accurate thermal analysis of a spacecraft is a process that should continue throughout development. It begins with simple calculations, often assuming spherical geometry and average values for solar heating, earth infrared radiation, earth albedo, and internal heat generation. These simple calculations provide rough estimates for the expected temperature ranges, which can then be used to design the first iteration of the thermal control system. Worst case hot and cold scenarios should be established, based on possible orbital parameters, attitudes, and the appropriate maxima and minima of external heat flux ranges. This system is then included in a more detailed computer model of the spacecraft, which is analyzed using a finite difference or finite element program. The program generates a nodal temperature distribution throughout the spacecraft, and thus indicates whether any component endures temperatures outside of operational range, which would require a redesign of the thermal control system. In order to assess the validity of the thermal model, the spacecraft should undergo thermal testing in a vacuum chamber. The boundary conditions of the testing chamber should be implemented in the thermal analysis program, and the results compared with those of the test. Any discrepancies should be included in subsequent simulations, particularly those which model the environmental fluxes of the proposed orbit. The result is an adequate thermal control system which will ensure that all components are operational during flight and bolster the success of the mission.

References

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