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# THERMAL DESIGN AND ANALYSIS OF A SMALL SATELLITE OPERATING IN LOW EARTH ORBIT

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## ABSTRACT

The duty of a satellite thermal control system is to maintain the temperatures of all satellite components within their allowable operational temperature limits, throughout the satellite mission. The thermal control methods are classified as passive and active. This paper presents the thermal design and analysis of a small satellite operating in Low Earth Orbit (LEO), having a passive thermal control system, and using thermal control hardware such as space qualified paints. The results, depicting the time variation of temperatures of major satellite components, show that all components operate within their safe temperature limits. The results also indicate the adequacy of design methodology, which can be used for the design and analysis of similar satellites, having identical mission requirements and orbital parameters.

**Keywords:** Thermal control system, Paints, Radiator, Spin rate, Solar panels, Batteries, Electronic box.

## 1. INTRODUCTION

All satellite components must work within their allowable temperature limits throughout the satellite mission. A satellite thermal control system is designed to perform this task. Depending on the design and operational factors, a passive or an active thermal control technique may be selected. However, passive method is preferable when simplicity, cost and reliability are the key design considerations.

The external surfaces of a satellite, radiatively couple the satellite to the deep space. These surfaces (radiators) are also exposed to external sources of energy such as direct solar flux, albedo (reflected solar radiation) and Earth-emitted IR. The radiating power of a radiator depends on its surface emittance and temperature, given by the following equation [1]:

$$\dot{Q} = A\varepsilon\sigma T^4 \qquad (1)$$

where $A$ is the radiator surface area ($m^2$), $\varepsilon$ is infrared emittance of radiator surface, $\sigma$ is the Stefan-Boltzmann constant ($5.669 \times 10^{-8}$ $W/m^2\,K^4$), and $T$ is the absolute temperature (K) of the radiator.

Radiators are given surface finishes with high infrared emittance and low solar absorptance, such as white paints ($\varepsilon > 0.8$, $\alpha < 0.2$), to maximize heat rejection from the radiator, and limit absorbed heat loads from the surroundings [2]. The $T^4$ term in the above equation, results in a large increase in radiating capability with temperature. Radiator temperature is sensitive to steadiness of power rejected, and approximately 1W of energy produces about 1K temperature change [3, 4].

In the process of satellite thermal design, a very important issue that the thermal designer has to address pertains to estimating the size and position of satellite radiator(s) [5]. The final number of radiators, their size and positions can be decided only after a thorough thermal analysis, considering the different orbital conditions (worst hot and cold cases), the radiator heat duty (amount of heat that must be dissipated by the radiator) and the satellite architectural design.

This paper presents the thermal design and analysis of a small cubic satellite operating in Low Earth Orbit (LEO). Based on the satellite mission requirements, a passive thermal control system has been designed. In this system, suitable space qualified thermal control hardware such as paints are used to achieve the required thermal control action. In order to reduce the satellite mass and cost, and increase design reliability, passive structural radiators have been considered for use.

## 2. THERMAL MODELING

The thermal control subsystem design is driven by the design of two passive structural radiators, situated on the top and bottom sides of the satellite (TOP and BASE plates). Our thermal control philosophy is based on control of the thermo-optical properties of all surfaces by means of paints and/or materials with well-known characteristics. Therefore, the radiators have been painted white ($\varepsilon > 0.8$, $\alpha < 0.2$). Solar cells placed on CFRP honeycomb panels with an aluminum core are attached on all lateral sides of the satellite on top of the aluminum walls. Figure 1, shows the satellite in $\beta = 60^{\circ}$ orbit, where $\beta$ is the angle between the solar vector and the orbit plane. Table 1 gives the direction the TOP radiator and the BASE radiator face.

Table 1: Direction of the two faces of the platform

| Reference Frame Direction | Name of Platform Side | Facing Direction/Name of Platform Side |
|---|---|---|
| -Z | BASE Plate | NADIR/Launcher I/F Side |
| +Z | TOP Plate | ZENITH/GG-Boom Deployment Direction |

The important orbital parameters are:

- Orbit inclination = 85º
- Orbit Eccentricity = 0 (Circular Orbit)
- Orbit Height = 1000 km
- Orbit Period = 105 Min. (6307 Sec)

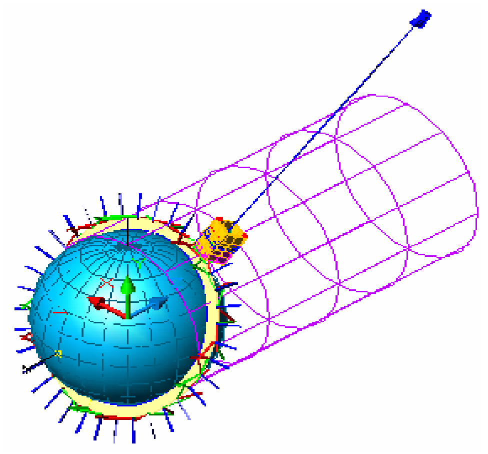

Fig 1: The satellite in the orbit with β = 60º

A simplified model of the satellite has been used for determination of the orbital worst hot and cold cases. The satellite has a slow spin (5 RPO) about its Z-axis. Table 2, shows the minimum and maximum values of orbital constants, used for cold and hot cases calculations, respectively.

Table 2: The minimum and maximum values of orbital constants used in this analysis [1]

| Orbital Constant | Minimum Value ($W/m^2$) | Maximum Value ($W/m^2$) |
|---|---|---|
| Solar constant | 1309 | 1400 |
| Albedo constant | 0.3 | 0.46 |
| Earth IR | 195.6 | 246.1 |

The modeling involves two mathematical models; a Geometrical Mathematical Model (GMM) (Fig.2), and a Thermal Mathematical Model (TMM). The GMM, which consists of submodels such as Electronic Box (E-Box), Telemetry Units, Batteries, Structural elements and Solar panels, is used to calculate the view factors and the environmental heat fluxes. The TMM is used to calculate the satellite temperatures. The system under consideration is transient, and hence, a transient thermal analysis, based on numerical implicit Forward-Backward method, has been used. The heat balance for a diffusive node is given as [6]:

$$\frac{2C_i}{\Delta t}\left(T_i^{n+1}-T_i^n\right) = 2Q_i + \sum_{j=1}^{N}\left[G_{ji}\left(T_j^n-T_i^n\right)+\hat{G}_{ji}\left\{\left(T_j^n\right)^4-\left(T_i^n\right)^4\right\}\right] + \sum_{j=1}^{N}\left[G_{ji}\left(T_j^{n+1}-T_i^{n+1}\right)+\hat{G}_{ji}\left\{\left(T_j^{n+1}\right)^4-\left(T_i^{n+1}\right)^4\right\}\right] \quad (2)$$

| | |
|---|---|
| $T_j$ | Temperature of thermal node *j* at current time *t* |
| $T_j^{n+1}$ | Temperature of thermal node j at current time *t+Δt* |
| $G_{ji}$ | Linear conductor for connecting the diffusion thermal node *j* to thermal node *i* |
| $\hat{G}_{ji}$ | Radiative conductor for connecting the diffusion thermal node *j* to thermal node *i* |
| $C_i$ | Heat capacitance of the diffusion thermal node *i* |
| $Q_i$ | Heat Source/Heat Sink for diffusion thermal node *i*. |

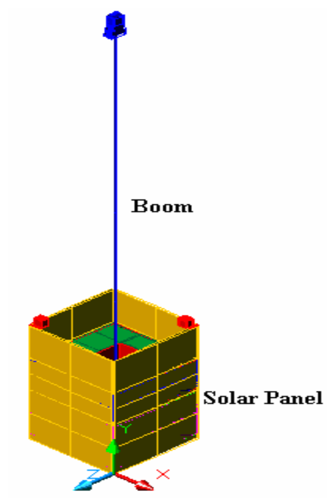


Fig 2: The geometrical mathematical model (GMM) of the satellite considered in this study

Table 3, presents components allowable temperature limits, and Table 4 shows their heat dissipations. Batteries have the tightest working temperature limits, and the telemetry units have high heat dissipation at transmission time. In this analysis, two possible operation modes have been considered; the nominal operational mode, in which all components dissipate their maximum heat, and the safe mode, in which one of the telemetry units will be off and hence has no heat dissipation. Table 5, presents the margin philosophy applied to this analysis.

Table 3: Components allowable temperature limits

| Unit | **Operative Range** (°C) | **Non-Operative Range** (°C) |
|---|---|---|
| Solar Panels | -50 ,+120 | — |
| Battery Pack | -5 ,+25 | -15,+40 |
| Electronic Box | -10 ,+50 | -40,+80 |
| Telemetry Units (UHF/VHF) | -5 ,+50 | -50,+50 |
| Structure | -80,+80 | — |

Table 4: Heat dissipation of satellite components in the two operational modes

| **Main Dissipating Components** | **Power Dissipation in Nominal mode (W)** | |
|---|---|---|
| | Hot case | Cold case |
| Battery (2 packs) | 5.5 x 2 | 0 |
| UHF Unit | 22.5 (10 Min.) | 0 |
| VHF Unit | 22.5 (10 Min.) | 22.5 |
| Electronic Box (E-Box) | 12 | 12 |

Table 5: Design margin philosophy used in the analysis

| Margin | Applied on: |
|---|---|
| ±10 ºC | Hot/Cold case temperature results for units without active control |
| -5 ºC | Cold case temperature controlled by heaters and thermostats |

## 3. RESULTS OF THERMAL ANALYSIS

### 3.1 Hot Nominal Operational Mode

Figure 3, shows the variations of batteries temperatures. The maximum temperature is about 19°C, which on consideration of a +10°C safety margin is just outside the allowable limits (Table 3).

Figure 4, presents temperature variation of the UHF. The unit has a maximum temperature of about 39°C, which occurs at the time of highest heat dissipation during transmission. However, even on consideration of a +10°C temperature safety margin, the temperatures are still within the allowable limits (Table 3). Variation of E-box temperatures is shown in Fig. 5. The maximum E-Box temperature is well within the allowable limits (see Table 3).

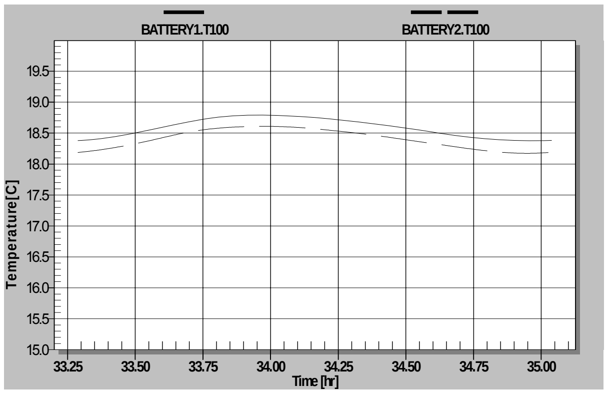


Fig 3: Variation of temperatures of batteries (hot nominal operational mode)

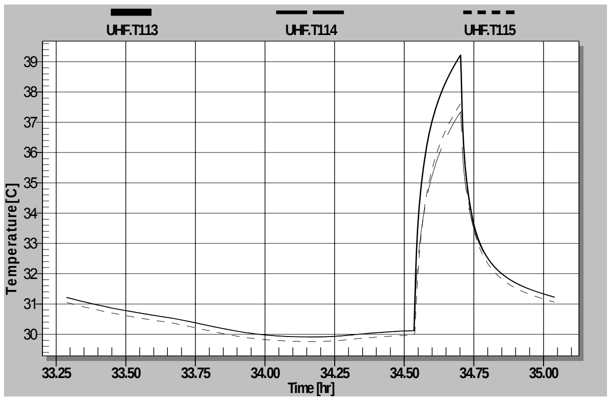


Fig 4: Variation of UHF temperatures (hot nominal operational mode)

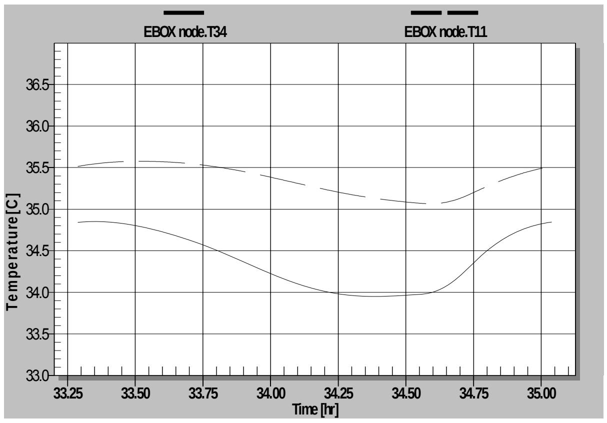


Fig 5: Variation of E-Box temperatures (hot nominal operational mode)

### 3.2 Cold Nominal and Safe Operational Modes

Figure 6, shows the variation of batteries temperatures for cold nominal and safe operational modes without heaters. The temperatures are below the minimum allowable limit, and heaters must be used for heating the batteries to their safe operating temperatures.

Figure 7 shows the improvement in the batteries temperature with heaters. Our estimation shows that a total heating power of 10W is adequate for this purpose.

The variations of the telemetry unit 1 temperatures for cold nominal and safe operational modes are shown in Fig. 8. The temperatures are within the safe operating limits. Figure 9, presents the temperatures variations of the E-Box for cold nominal and safe operational modes. Considering Table 3, the temperatures of this unit are satisfactory.

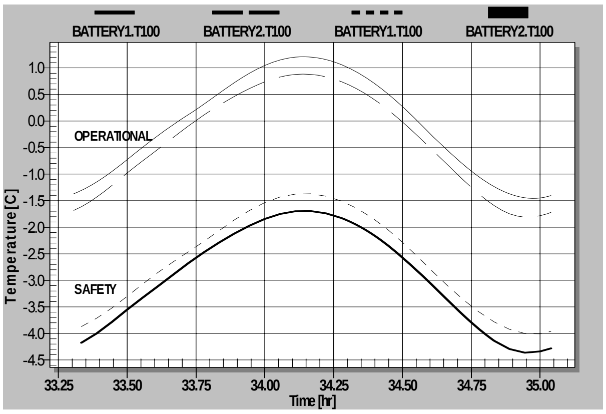


Fig 6: Batteries temperatures (cold nominal and safety operational modes, without heaters)

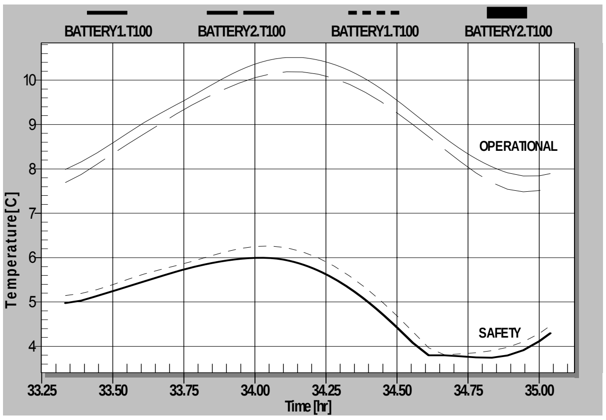


Fig 7: Batteries temperatures (cold nominal and safety operational modes, with heaters)

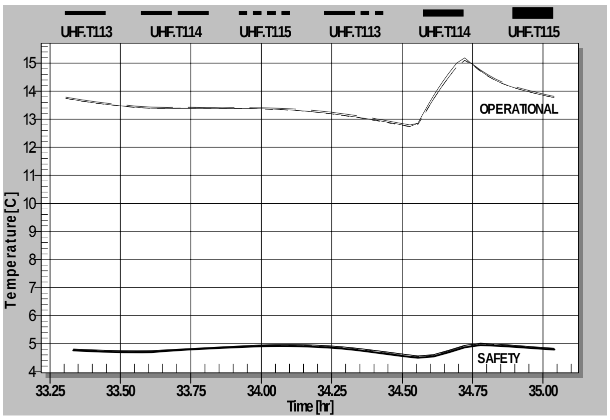


Fig 8: UHF temperatures (cold nominal and safety operational modes)

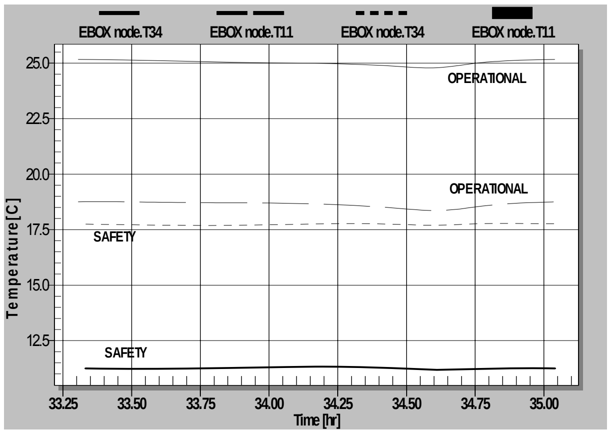


Fig 9: E-Box temperatures (cold nominal and safety operational modes)

## 4. CONCLUSIONS

In this paper, thermal design and analysis of a small satellite operating in LEO orbit has been presented. Two radiators have been designed to reject heat to the deep space. Temperature results, particularly battery temperatures, indicate that in the nominal operational mode, temperatures are just above the maximum allowable value, and using a single radiator will not be sufficient to keep the batteries within safe temperature limits. Therefore, the decision for using two radiators is well justified. For the cold case, however, the battery temperatures fall below the minimum allowable value, needing heaters to maintain battery temperatures within safe limits. Our estimation shows that a total of 10W is adequate for this purpose. The results also indicate the adequacy of the methodology and procedure followed in this work, which can be used for the thermal design and analysis of similar satellites, having identical mission requirements and orbital parameters.

## 5. REFERENCES


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