

SENSITIVITY ANALYSIS FOR ASSESSMENT OF EFFECT OF UNCERTAINTIES IN ENVIRONMENTAL AND PHYSICAL PARAMETERS ON SATELLITE TEMPERATURE PREDICTIONS

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ABSTRACT

Temperature is the most important thermal control parameter in any satellite. In the analytical process of satellite temperature prediction with a thermal mathematical model, a number of inaccuracies exist which lead to temperature uncertainties. The reduction of the uncertainty during the course of a space project is the consequence of applying more detailed and accurate models, and improved knowledge of the physical data used. The impact of various inaccuracies on the temperature predictions can be assessed using an adequate sensitivity analysis. In this paper, typical inaccuracies in some important environmental and physical parameters have been considered, and a sensitivity analysis has been performed, on the basis of the satellite thermal mathematical model used for nominal temperature predictions. In this analysis, the nominal parameter values have been replaced by values including the assumed inaccuracies, and the effects of these inaccuracies on the satellite temperature predictions have been assessed. The results of this study have been used in the temperature predictions of a microsatellite.

Keywords: Thermal control, Temperature Uncertainty, Inaccuracy, Environmental Parameters, Physical Parameters, Sensitivity Analysis,

1. INTRODUCTION

Temperature is the most important thermal control parameter in any satellite thermal control subsystem. In the analytical process of temperature prediction with a thermal mathematical model, there are a number of inaccuracies due to the level of modeling, available physical data, and lack of precise definition of the item under consideration and its environment. These inaccuracies result in temperature uncertainties which should be considered on top of the calculated temperature range. The calculated temperatures increased or decreased by the appropriately assessed uncertainties shall be equal to or less than the thermal control subsystem design temperatures.

Thermal uncertainty associated with temperature predictions is reduced during design-analysis-test process as the design becomes more robust, as improved and more detailed analyses are conducted, as more accurate physical and environmental parameters are used, and as developmental tests are completed. The thermal balance test and subsequent correlation of the analytical model to test data, reduces temperature-prediction

uncertainty to a large extent. Deviation between on-orbit temperature measurements and preflight temperature measurements and preflight temperature predictions is a measure of the final uncertainty associated with the satellite thermal analysis and test.

1.1 Thermal Uncertainty Margin

In practice, even with the best available analysis tools, accurate and refined spacecraft design information, and carefully specified materials properties, spacecraft thermal analysis does not provide the level of precision customary in other disciplines.

The thermal uncertainty margin is a margin of safety applied to worst-case analytic temperature predictions (from all mission phases) to account for uncertainties inherent in parameters such as complex view factors, surface properties, radiation environment, joint and interface conduction, and ground simulation [1].

Experience shows that carefully developed models, correlated with preflight thermal test data, offer an accuracy band of only about $\pm 10\text{K}$ [2]. This is the basis for MIL-STD-1540B requirement for a band of $\pm 11\text{K}$ to

achieve 95% confidence that flight temperatures will be within predicted preflight tolerances [3, 4]. When accurate thermal-balance tests cannot be performed, a tolerance of $\pm 17\text{K}$ is recommended [2].

It is usually best to view design temperature margin requirements (mentioned above), as being functions of the space program life cycle [5]. For example, at the concept of design stage, it might be expected that the thermal system be capable of handling a heat load of up to 50% greater than analytically predicted. This allows substantial change in the spacecraft design without having an adverse effect on the thermal control system. Because such changes rarely are in a favorable direction, an initially comfortable 50% margin will decrease as launch is approached, at which point a 20% margin may well be considered adequate [6].

1.2 Sources of Temperature Uncertainties

Uncertainties in spacecraft temperatures predictions are caused by inaccuracies associated with the following categories of data [6]:

- Environmental parameters
- Physical parameters
- Modeling parameters
- Test facility parameters

In order to simplify the analysis, we have kept the parameters to a minimum, by considering only the first two categories.

Environmental Parameters

The inaccuracies in environmental parameters and the associated uncertainties are due to the following:

- Solar and planetary radiation values
- Orbital and altitude parameters
- Aerothermal fluxes

The quantities used during the nominal thermal analysis for the solar, planetary Albedo and planetary infrared radiation are not necessarily the extreme values which an item can be subjected to during its lifetime. Therefore, sensible variations around the nominal values shall be applied to these parameters. This is particularly relevant for items with low time constants. To simplify the analysis, we have considered only the inaccuracies in solar and planetary radiation values.

Physical Parameters

The inaccuracies in physical parameters and the associated uncertainties are due to the following data:

- Bulk and surface material properties
- Inter-material contact characteristics
- Dimensions
- Heat dissipations of units

The temperatures of an item in space are mostly controlled through conductive and radiative heat transfer paths. The above parameters which describe such paths are subject to inaccuracies which are due to measurement tolerances, manufacturing tolerances and in most cases a combination of both. To make the analysis traceable, we have considered only the inaccuracies in contact resistance and heat dissipation of units.

In a space project, depending on the project status, the considered parameter inaccuracies can vary in magnitude

and importance. We have used the parameter inaccuracies shown in Table 1, which are the parameter inaccuracies at the advanced project stages.

Table 1: Parameter inaccuracies [6]

a) Environmental Parameters	
Solar intensity	$\pm 21 \text{ W/m}^2$
Earth radiation	$\pm 65 \text{ W/m}^2$
Albedo factor	± 0.1
b) Physical Parameters	
Contact resistance between the component and the structure (by similarity)	$\pm 50 \%$
Heat dissipation in components (for absolute value $< 10\text{W}$)	$\pm 10 \%$

2. SENSITIVITY ANALYSIS

The impact of the applicable inaccuracies on the temperature predictions can be assessed via adequate sensitivity analyses. Based on the thermal mathematical model used for nominal temperature predictions, such sensitivity analyses shall be performed by replacing nominal parameter values by values including the expected or assumed inaccuracy. However, it is usually not needed, nor suitable to carry out as many analysis runs as individual parameters exist. In this paper, typical inaccuracies in some environmental and physical parameters (section 1.1) have been considered, and their effects on the satellite temperature predictions have been assessed. The result of such an analysis run will provide a specific temperature uncertainty (i.e. difference between actual temperature and nominal temperature) either as function of one parameter or of a group of parameters.

2.1 Overall Uncertainty of a Thermal Node Temperature

Specific temperature uncertainties due to inaccuracies in environmental and physical parameters are of statistical nature and can be summed up as root sum squared (RSS). The RSS provides information about the sensitivity of results to uncertainties in independent variables and the importance of each uncertainty in the overall system uncertainty. Therefore, it is useful in identification of critical variables [7]. The following simplified formula is used for determination of the overall uncertainty of thermal node i temperature, considering only temperature uncertainties due to environmental and physical parameters [6]:

$$(\Delta T_i)_{overall} = \sqrt{\sum_{j=1}^{n_e} (\Delta T_{e,j})^2 + \sum_{k=1}^{n_p} (\Delta T_{p,k})^2} \quad (1)$$

Where,

- $(\Delta T_i)_{overall}$ = Overall uncertainty of thermal node i temperature
- $(\Delta T_{e,j})_i$ = Temperature uncertainty due to environmental parameters j on node i

- $(\Delta T_{p,k})_i$ = Temperature uncertainty due to physical parameters k on node i
- n_e = Number of environmental parameters,
- n_p = Number of physical parameters

2.2 The Analysis Procedure

The following procedure was adopted:

1. The critical parameters from the categories of sources of uncertainty on spacecraft temperatures predictions (section 1) were identified. This reduces time, cost and simplifies the analysis.
2. For each category, to include the assumed inaccuracies, a value from Table 1 was added to the nominal value of each of the above parameters.
3. The new value obtained from step-2 was then used in a thermal mathematical model (see next section), and new temperature predictions were obtained.
4. Applying steps 2 and 3 repeatedly, new temperature predictions were obtained for each category.
5. Equation (1) was then used for the determination of the overall uncertainty in the predicted temperature of each component, by adding the individual temperature uncertainties due to the parameters.

3. MODELING AND THERMAL ANALYSIS

The typical satellite considered (Fig. 1) is a small cubic satellite, in which the outer surface of the bottom plate faces the Nadir (towards the earth), and the outer surface of the top plate faces the Zenith. The middle plate divides the satellite into two separate sections.

The satellite orbit is a sun-synchronous orbit, i.e., the β angle, which is the minimum angle between the orbit plane and the solar vector, is nearly constant throughout the satellite mission [1]. Figure 2, shows the satellite in the orbit with $\beta = 60^\circ$. The other parameters of the considered orbit are:

- Inclination angle = 99°
- Eccentricity = 0 (circular orbit)
- Altitude = 900 km

The first step in the thermal analysis is performed by constructing two mathematical models; a geometrical mathematical model (GMM) and a thermal mathematical model (TMM), using *Thermal Desktop* and *SINDA/FLUINT* software, respectively. The two mathematical models consist of the followings submodels:

- The electronic box (E-Box),
- The telemetry unit,
- The battery, and
- The satellite structure and solar panels.

The geometrical mathematical model is used to determine:

- The view factors of the internal components relative to each other, and the satellite external surfaces relative to the space,

- The environmental heat fluxes (solar flux, earth albedo and Infrared radiation) on the satellite surfaces.

Outputs from the geometrical model and the heat dissipation in different components of the satellite (see Table 2) have been used as inputs in the thermal mathematical model to determine the temperatures of various surfaces and components.

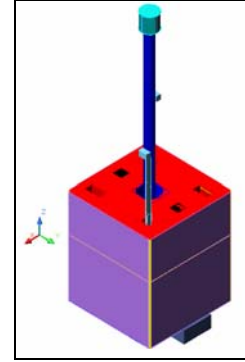


Fig 1. The satellite model (boom not scaled)

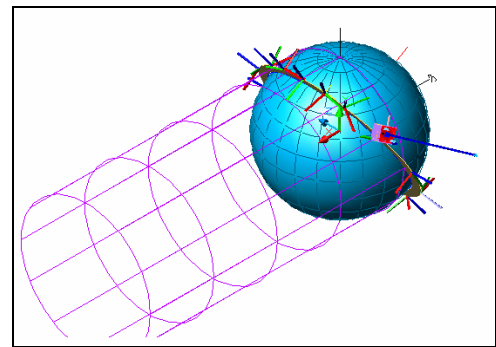


Fig 2. The satellite, in an orbit with $\beta = 60^\circ$

Table 2: Heat dissipation in the satellite components

Component	Dissipation [W] (Hot case)
E-Box	9.75
Telemetry Subunits (2 nos.)	22.5 x 2 (for 20 min.)
Battery Packs (2 nos.)	2 x 2

4. RESULTS AND DISCUSSION

In the following sections, we discuss the results obtained from the sensitivity analysis.

Figure 3, shows the time variation of temperatures for the bottom, middle and top plates in the satellite structure. The outer surface of the bottom plate is covered with multilayer insulation (MLI), and the maximum heat dissipation (E-Box and telemetry unit heat dissipation) occurs in the lower section of the satellite, therefore, the temperature of bottom plate is higher than the other plates, and the middle plate temperature is higher than that of the top plate (the top plate acts as the satellite radiator).

Figures 4 through 13, show the effect of uncertainties in values of contact resistance (R_{cont}), components internal heat dissipation and the environmental parameters (solar, albedo and earth IR), on temperature predictions for the components considered. For drawing each figure, two uncertainty values have been considered for any of the considered parameters; a positive and a negative value. In these figures, the third curve shows the temperature of the component, predicted using the nominal value of the parameter.

We have applied Eq. (1) to estimate the overall uncertainty of the predicted temperatures for the battery, the telemetry unit and the E-Box temperatures, considering the uncertainty values in Table 1.

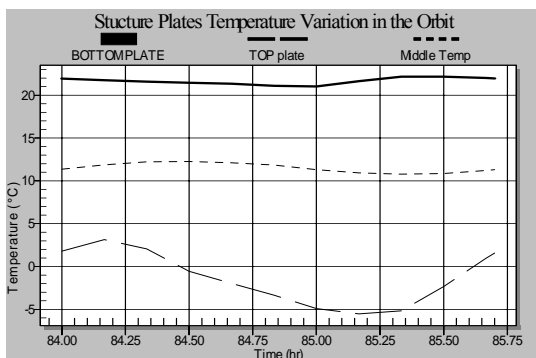


Fig 3. Temperature variation of structural units

4.1. Effect of Uncertainties in Contact Resistance Value on Temperature Predictions

Figure 4, shows the variation of battery and middle plate temperatures for nominal value of the contact resistance (R_{cont}). Figure 5, shows the variations of battery temperature with uncertainty in contact resistance value.

Considering Figs. 4 and 5, it is evident that for the nominal value of contact resistance, the battery temperature is a little lower than temperature of the middle plate, and hence the heat flow direction is from middle plate to the battery. As shown in Fig. 4, an increase in contact resistance (decreased conductance) between the battery and the middle plate decreases the heat flow from the warmer middle plate to the cooler battery. This reduced heat transfer, results in a reduction in the battery temperature as compared to its initial value. On the other hand, a reduction in contact resistance (increased conductance), increases heat flow from the battery to the middle plate. This increased heat transfer, increases the battery temperature compared to its initial value. However, as shown, the battery temperature is not sensitive to the uncertainty in contact resistance value, and that the maximum temperature uncertainty has been estimated to be 0.7°C .

Figure 6, shows the variation of the E-box temperature with uncertainty in contact resistance value. The increased contact resistance (decreased conductance) results in an increase in the E-Box temperature, because the flow of dissipated heat in the E-Box, to the bottom plate, has decreased as a result of

increased contact resistance. As expected, when the contact resistance decreases (increased conductance), the E-Box temperature decreases as shown in Fig. 6. However, the E-Box temperature is not quite sensitive to the uncertainty in contact resistance value, and that the maximum temperature uncertainty estimated is 1.7°C .

Figure 7, shows the variation of the telemetry unit temperature, with uncertainty in contact resistance value. The telemetry unit temperature has increased with the increase in contact resistance. This is due to the decrease in the flow of heat, dissipated during the peak in the operational phase of the telemetry unit. The temperature peaks in the figure show this condition. However, the telemetry unit temperature is sensitive to the uncertainty in contact resistance value, and that the maximum temperature uncertainty has been estimated to be 3.2°C .

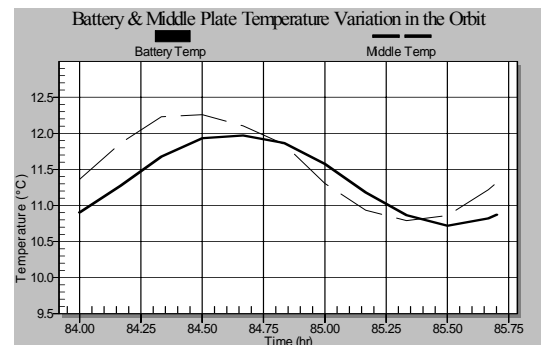


Fig 4. Variations of battery and mid-plate temperatures for nominal contact resistance value

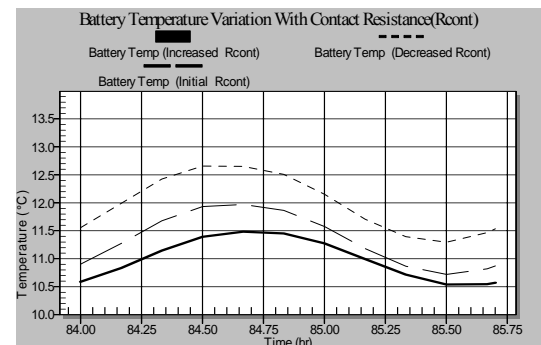


Fig 5. Variations of battery temperature with uncertainty in contact resistance values

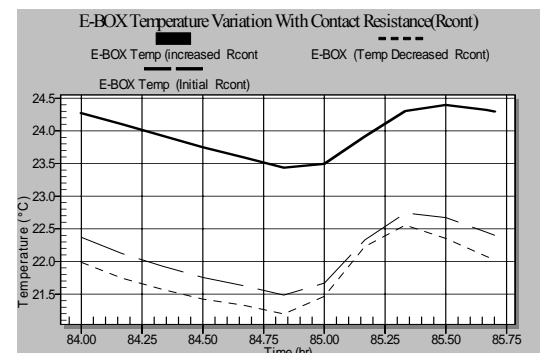


Fig 6. Variations of E-Box temperature with uncertainty in contact resistance values

Figure 7, shows the variation of the telemetry unit temperature, with uncertainty in contact resistance value. The telemetry unit temperature has increased with the increase in contact resistance. This is due to the decrease in the flow of heat, dissipated during the peak in the operational phase of the telemetry unit. The temperature peaks in the figure show this condition. However, the telemetry unit temperature is sensitive to the uncertainty in contact resistance value, and that the maximum temperature uncertainty has been estimated to be 3.2°C.

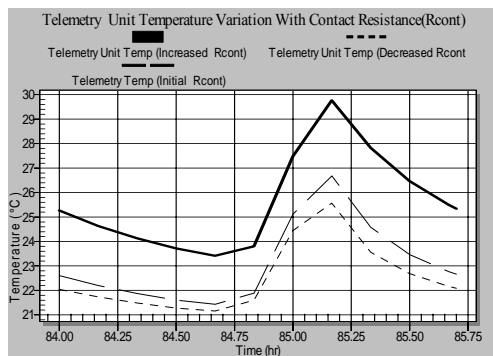


Fig 7. Variation of telemetry unit temperature with uncertainty in contact resistance values

4.2 Effect of Uncertainty in Heat Dissipation Value on Temperature Predictions

Figure 8, shows the variation of battery temperature with the uncertainty in internal heat dissipation value. As expected the battery temperature increases with the positive value of uncertainty in the internal heat dissipation. This is because of a greater amount of heat which has to be transferred to the middle plate for the same contact area, which results in an increase in the temperature of the battery. The battery temperature is sensitive to the uncertainty in the internal heat dissipation value, and that the maximum temperature uncertainty has been estimated to be 2.3°C.

Figure 9, shows the variation of the E-Box predicted temperature with uncertainty in internal heat dissipation value. The E-Box temperature increases with the positive value of uncertainty in the internal heat dissipation. This is because of greater heat dissipation in the E-Box, and also a greater amount of heat transferred from the telemetry unit to the E-Box during the peak in the operational phase of the telemetry unit. This greater amount of heat will have to be transferred to the bottom plate for the same contact area, which results in an increase in the temperature of E-Box. The E-Box temperature is sensitive to the uncertainty in the internal heat dissipation value, and that the maximum temperature uncertainty has been estimated as 2.1°C.

Figure 10, shows the variation of the telemetry unit predicted temperature with uncertainty in internal heat dissipation value. As expected the telemetry unit temperature increases with the positive value of uncertainty in the internal heat dissipation. This is due to the increase in the internal heat dissipation at its peak operational phase, which results in an increased

temperature. The telemetry unit temperature is quite sensitive to the uncertainty in the internal heat dissipation value, and that the maximum temperature uncertainty has been estimated to be 3.3°C.

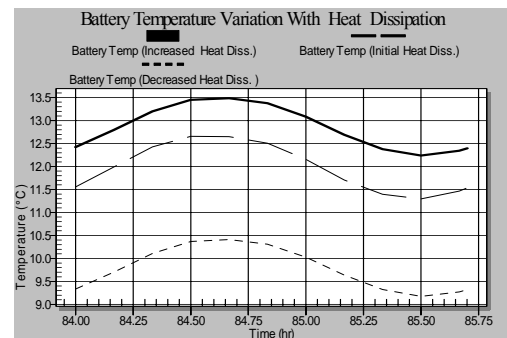


Fig 8. Variation of battery temperature with uncertainty in internal heat dissipation values

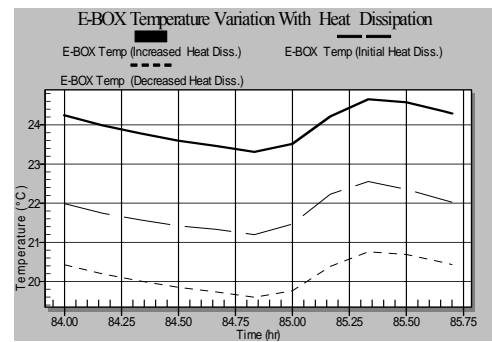


Fig 9. Variation of E-box temperature with uncertainty in internal heat dissipation values

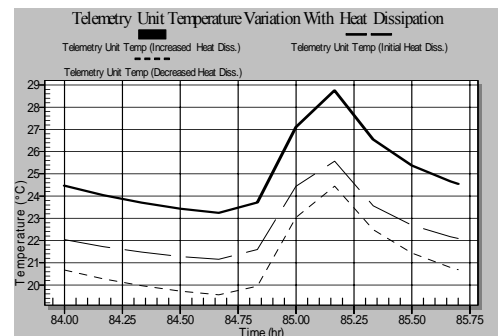


Fig 10. Variation of telemetry unit temperature with uncertainty in internal heat dissipation values

4.3 Effect of Uncertainties in Environmental Parameters Value on Temperature Predictions

The variations of battery predicted temperature, with uncertainties in solar flux, albedo and earth IR values are shown in Fig. 11. As shown, the battery temperature is sensitive to the uncertainty in environmental parameters values, and that the maximum temperature uncertainty has been estimated to be 2.1°C.

Figure 12, shows the variations of E-Box predicted temperature, with uncertainties in solar flux, albedo and

Earth IR values. The uncertainty on the E-Box due to the uncertainties in environmental parameters considered has been estimated to be 3.1°C, which shows this component is quite sensitive to the uncertainties in environmental parameters.

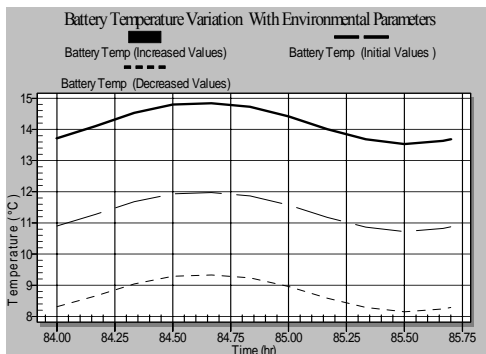


Fig 11. Variations of battery temperature with uncertainty in solar, albedo and Earth IR values

The variations of the telemetry unit predicted temperature, with uncertainties in solar, albedo and Earth IR values are shown in Fig. 13. The uncertainty on the telemetry unit due to the uncertainties in environmental parameters considered has been estimated to be 3.0°C, which shows this component is quite sensitive to the uncertainties in environmental parameters.

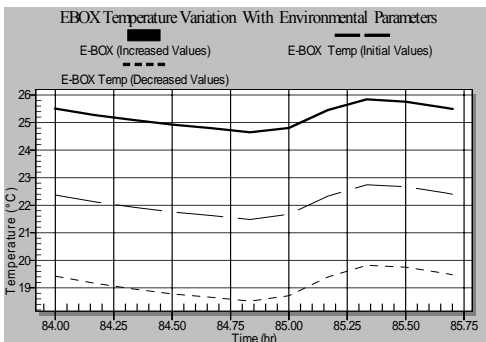


Fig 12. Variations of E-Box temperature with uncertainty in solar, albedo and earth IR values

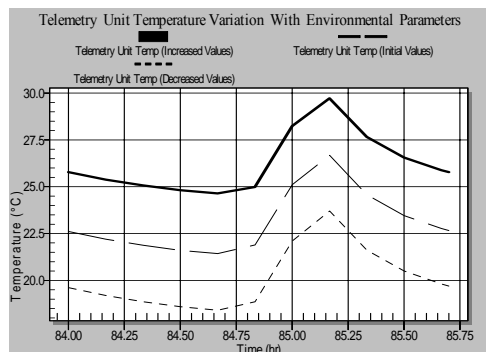


Fig 13. Variations of telemetry unit temperature with uncertainty in solar, albedo and earth IR values

5. CONCLUSIONS

The following conclusions can be made:

- ✓ The estimated values of overall temperature uncertainties for the battery, the telemetry unit and the E-Box are 3.70°C, 5.50°C and 4.11°C, respectively.
- ✓ For the sake of simplicity and ease of tracing the effects of various parameters on the overall uncertainty, we have considered only some of the influencing factors. To accurately calculate the final uncertainty of the predicted temperatures for the designed system, a more thorough sensitivity analysis is needed. Such an analysis should consider all the applicable inaccuracies, including modeling and test facility parameters.
- ✓ For the satellite considered in this study, the effect of uncertainties in the environmental parameters (solar, albedo, Earth IR) on the overall uncertainty of the predicted temperatures is more pronounced.
- ✓ Among the physical parameters, internal heat dissipation has a greater influence on the overall uncertainty. However, equal attention must be paid for the estimation of uncertainties in both the parameters in this category.
- ✓ The results of this study have been used in the temperature predictions of a microsatellite.

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