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THE THERMAL MODEL CORRELATION OF THE STRUCTURAL THERMAL QUALIFICATION MODEL OF GEOSTATIONARY SATELLITE

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ABSTRACT

This paper discusses and outlines correlation of thermal mathematical model (TMM) of structural thermal qualification model (STQM) of indigenous satellite, which is a Geostationary Telecommunication satellite with Ku-Band, X-Band and telemetry/tele-command payload. Thermal Mathematical Model (TMM) and Geometrical Mathematical Model (GMM) of satellite STQM are explained. The TMM is run in MSC THERMICA for three thermal test cases by creating the similar test configurations. The first Thermal Balance Test cases is; TBT 1/2 which simulates the worst hot case of satellite being a significant design scenario for radiator and heat pipe sizing. The second balance case is TBT 4, which simulates the safe mode (minimum heat dissipation) of satellite being critical for heater power calculation. The final test case (TBT 3b) is a time dependent case being realized for measuring adequacy of radiator areas, heaters and capacitance of batteries. The properties are described and iteratively modified in TMM until the test success criteria are achieved. The comparison of results for each test case and TMM final temperature results are tabulated.

Keywords: Thermal Mathematical Model (TMM), Geometrical Mathematical Model (GMM), Structural Thermal Qualification Model (STQM), Thermal Mathematical Model (TMM) and Thermal Balance Test (TBT)

INTRODUCTION

TCS (Thermal Control Subsystem) keeps subsystem equipment temperatures at required temperature levels using equipment qualification temperatures and margins defined in ECSS standards [ESA-ESTEC, 2008]. This document is focused on the mathematical model correlation of satellite STQM which includes the comparison of the STQM Thermal Mathematical Model analysis results and the Thermal Balance Test results.

GEO satellite modules and thermal hardware used are defined under the three separate divisions, which are Payload Module, Platform Module and Propulsion Modules. In the STQM, structural and thermal dummies are integrated which simulate the thermal and structural

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characteristics of real functional equipment. The heat dissipations of equipment are simulated via heaters on these dummies.

The interfaces of dummies are exactly the same as flight equipment however there are some deviations from real thermo-optical properties capacitances, physical volumes and thermal conductivities.

Three divisions, Payload Module, Platform Module and Propulsion Module, are explained as follows.

Payload Module:

Payload module of STQM includes North Communication, South Communication and Earth Communication panels. Heat flow at the earth panel antenna interfaces, are simulated with dummy heaters on plates under the MLI's. Yellow geometries represent MLI zones at the external side of STQM panels and blues represent embedded heat pipes at the North and south communication panels. (Figure 1) North and south communication panels are aluminium honeycomb panels. All of the radiator areas on STQM are simulated with white paint.

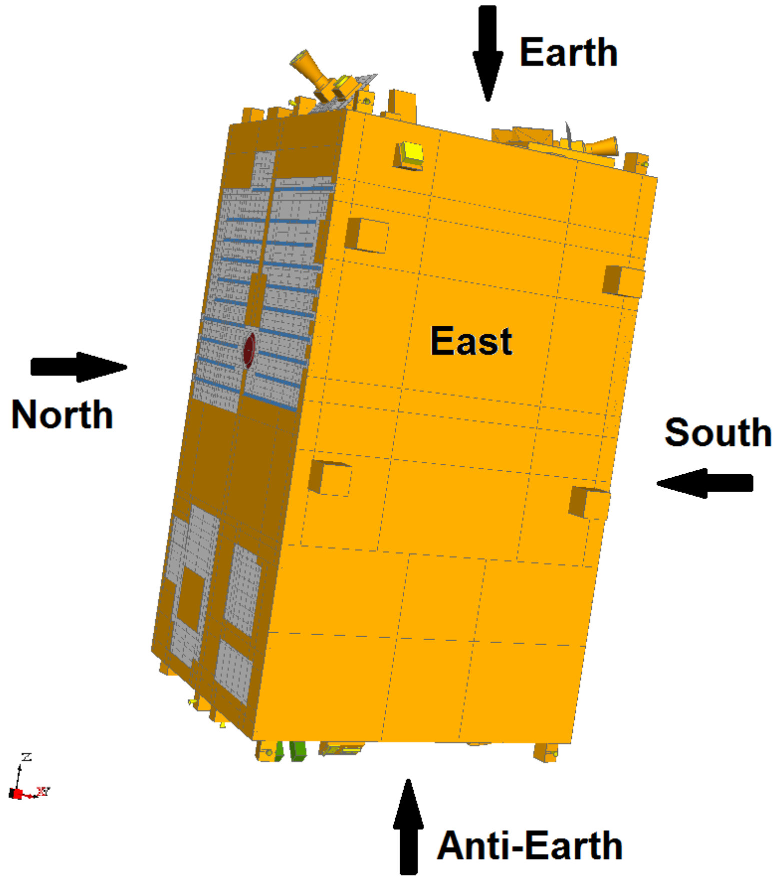

Figure 1 : General GMM Demonstration of STQM

TCS Heaters are located on the heat pipes, which is the main concern for the heater alignment, to diffuse heat to the more extensive areas [Gilmore, 2002]. At the thermal mathematical model (TMM) heater powers are assigned to the nodes whose locations are the same as the 3D CAD heater models [NASA, 2000]. Most the X-Band subsystem equipment, portion of Ku-Band subsystem equipment and two gyroscopes are located on the north communication panel. Most telemetry and tele-command subsystem equipment, portion of Ku-Band subsystem equipment are located on the south communication panel. Unlike to the north communication panel, south communication panel has an internal MLI on the Ku-Band receivers.

Platform Module:

Platform module contains east, west and all service panels of the STQM. Most of the platform equipment is located on north and south platform panels; on radiator areas. North and south platform panels are aluminium honeycomb panels. Battery 1, On-Board Computer, Electrical Propulsion and Power Distribution Unit and Experimental Reaction Wheel with its electronic part are located on the north platform panel. Surface mouthed heat pipes (SMHP) are used for platform module equipment except for batteries. Since the only contact occurs from SMHP to the panel and equipment at the flange portions, flangeless portions of SMHP are not modelled in geometrical mathematical model (GMM). There is zero contact and negligible irradiation at the flangeless portions of SMHP's. Power Regulation and Control Unit, Power Distribution Unit and Battery 2 are located on the south platform panel. For surface mounted heat pipes, only the parts with flange are modelled on the GMM of south service panel as for north service panel.

Propulsion Module:

Propulsion subsystem has its own active and passive thermal control hardware. TCS is responsible from controlling the interfaces of propulsion subsystem from thermal point of view. The supplier provides the thermal mathematical model of CPS (Chemical Propulsion System) flight configuration. All supplied data is converted to the STQM configuration (dummy properties defined) and implemented to the STQM.

Thermal Vacuum Chamber is required to be modelled before the analysis in order to simulate the test environment.

TVC Model:

Thermal mathematical model of Thermal Vacuum Chamber (TVC) is given in Figure 2. North and south calrod heaters, calrod supports, support frame and walkways and shrouds are the main components of TVC. During the TMM preparation of TVC, real physical material properties are assigned to the components for obtaining realistic results. Moreover, thermo-optical properties of components are assigned for radiative calculation. Materials and thermo-optical properties of TVC components are given in Table 1.

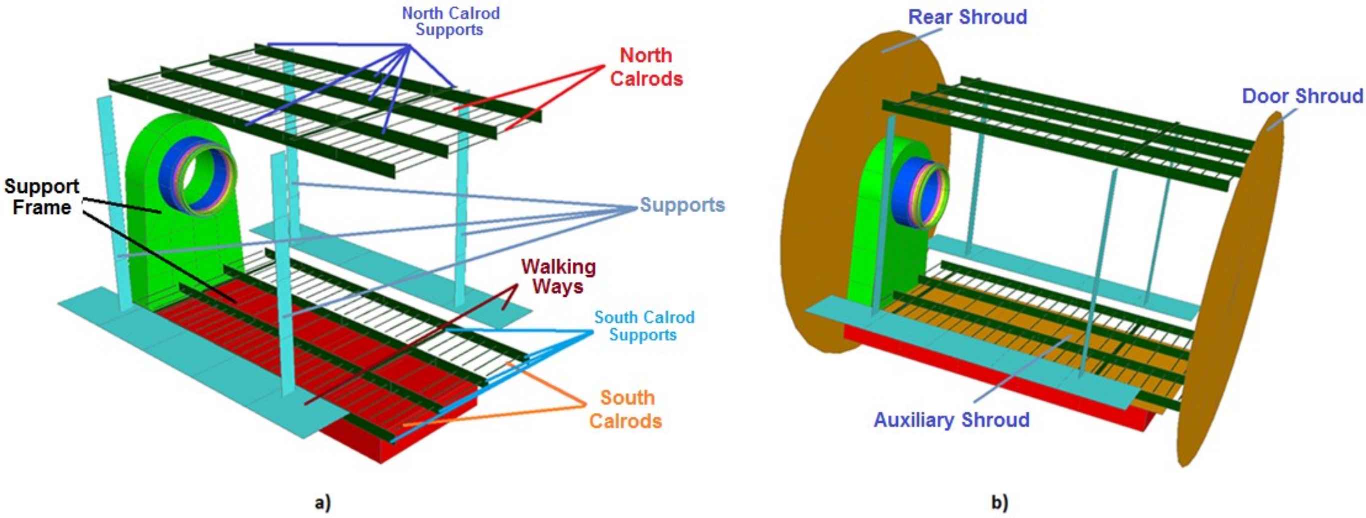

Figure 2: a) TMM of TVC without shrouds b) TMM of TVC with Rear, Door and Auxiliary shrouds

In order to avoid the heat transfer between support frame and STQM, support frame is covered with MLI.

Table 1 Components and Thermo-Optical Properties of TVC

Component	Material	Coating Material	Emissivity	Absorptivity
Rear Shroud	SS-304L	Aeroglaze	0.90	0.95
Door Shroud	SS-304L	Aeroglaze	0.90	0.95
Cylindrical Shrouds	SS-304L	Aeroglaze	0.90	0.95
Auxiliary Shroud	SS-304L	Aeroglaze	0.90	0.95
North / South Calrods	SS-304L	Calrod Coating	0.40	0.40
North / South Calrod Supports	SS-304L	Aeroglaze	0.90	0.95
Support Frame MLI	SS-304L	TAS_MLI	0.77	0.47
Thermal Adaptor	ALU-7010	TAS_MLI	0.77	0.47
Supports	SS-304L	Aeroglaze	0.90	0.95
Walking Ways	SS-304L	SS-304L-Unpolished	0.10	0.10

TVC test system is capable of cooling the shrouds down to -190 ℃ with the liquid nitrogen cycling. Boundary conditions assigned to the TMM of TVC are identified at Table 2.

Table 2 Used boundary conditions at the TMM of TVC

Component	Boundary Conditions
Rear Shroud	-190°C
Door Shroud	-190°C
Cylindrical Shrouds	-190°C
Auxiliary Shroud	-180°C
Support Frame	10°C
Thermal Adaptor	10°C

METHOD

Correlation study is performed between prepared TMM and test model for the three main test cases. These cases are,

1. Hot Case – Steady State (Balance) (IDT 1/2)
2. Cold Case (Safe Mode) - Steady State (Balance) (IDT 4)
3. Time Dependent Case – Equinox Simulation (IDT 3b)

At the hot case balance scenario, maximum number of equipment is operational. Hot case balance scenario is also defined as IDT 1/2. At the cold case, safe mode of satellite is simulated and this case is defined as IDT 4.

An iterative approach is followed during the correlation study. The contact conduction of equipment to panel, thermo-optical properties of radiator areas, MLI effective emissivity panel transversal conductance and conducted heat ratio of heaters to the panel are examined. These parameters directly affect the equipment temperature.

During the correlation studies, in case a change occurred at the identified parameters, both cold (IDT 4) and hot (IDT 1/2) cases are run again. This procedure is repeated till the aimed success criteria is achieved.

Time dependent case (IDT 3b) is realized for measuring adequacy of radiator areas, heaters and capacitance for battery. Battery temperature results for analysis and test cases are examined. Thermal interface parameters hardware of batteries; heater powers, radiator areas, contact values and capacitances are verified during these cases.

Main target of correlation study is to achieve the success criteria given in ECSS-E-ST-31C. ECSS-E-ST-31C [ESA-ESTEC, 2008] success criteria is given below:

1. Difference between measured and predicted temperatures need to be in the defined limits.
2. Mean deviation values need to comply with ECSS-E-ST-31C. Division of sum of temperature differences to the number of correlated equipment gives the mean deviation value. (Equation 1)

$$\Delta T_{mean} = \frac{1}{N}\sum_{i=1}^{N}(T_{Mi} - T_{Pi}) \qquad (1)$$

Parameters of Equation 1;

ΔT_{mean}: Average Deviation Value
T_{Mi} : Measured Temperature
T_{Pi} : Predicted Temperature (Analysis)
N : Number of Correlated Equipment

Calculated standard deviation values need to comply with ECSS-E-ST-31C [ESA-ESTEC, 2008]. Standard deviation is a statistical measurement value, which reflects whole temperature data and shows distribution of temperature differences. Plotted distributions are given in the conclusion.

Equation 2 shows the formula of standard deviation.

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}[(T_{Mi} - T_{Pi}) - \Delta T_{mean}]^2} \qquad (2)$$

Parameters of Equation 2;

σ : Standard Deviation Value
ΔT_{mean}: Average Deviation Value
T_{Mi} : Measured Temperature
T_{Pi} : Predicted Temperature (Analyse)
N : Number of Correlated Equipment

Objective values;

- Mean Deviation Value **±2K**
- Standard Deviation **<3K, 1σ**
- Typical maximum deviation (uncertainty values at the thermal analyses); for STQM; 10 K for internal equipment and 15 K for external equipment.
- For statistically meaningful results, at least 25 equipment temperatures needed for mean deviation and standard deviation calculations.
- Defined success criteria shall be achieved for both IDT 1/2 (hot) and IDT 4 (cold) cases. Calculated deviation values for equipment dummy temperatures are given in conclusion.

APPLICATION

General Information for Hot Case Correlation & Cold Case Correlation:
Used heater configurations for IDT 1/2 (hot case) and IDT 4 (cold case) and related heater definitions are given in Table 3. During analysis, test phase given heater configurations are used. IDT 1/2 simulates worst hot case of satellite, which is a significant design scenario for radiator and heat pipe sizing whereas IDT 4 simulates safe mode (minimum heat dissipation) of satellite, which is critical for heater power calculation.

Table 3 Heater Configuration

Configuration Item	Definition	Heater Statue (IDT1/2 & IDT 4)
Dummy Heaters	Dummy heaters provide required heat load for the contact conductance calculation, which specify heat transfer amount between dummy equipment to S/C panel.	IDT 1/2: Completely Open IDT 4: Partially Open
TCS Heaters	Thermal control heaters, which prevent dummy temperatures from decreasing, below the qualification limits.	IDT 1/2: Completely Close (For preventing any effect to the contact conductance calculation) IDT 4: Partially Open
Calrod Heaters	Calrod heaters simulate external fluxes to exterior side of S/C.	IDT 1/2: Completely Close (For preventing any effect to the radiator sizing) IDT 4: Completely Close (For preventing any effect to the heater power calculation)

Final mean deviation and standard deviation values of T6A STQM mathematical model correlation for IDT 1/2 and IDT 4 are given in
Table 4.

Table 4 IDT 1/2 Average and Standard Deviation Values

Scenario:	Average Deviation (ΔT_{ORT}) (K)	Standard Deviation (ΔT_{STD}) (K)
IDT 1/2	0.34	1.83
IDT 4	-0.05	1.77

Contact Conductance Calculation:
Heat transfer between panel and equipment is directly dependent on the interface filler material performance. Heat transfer of equipment is linearly proportional to contact conductance between panel and equipment. In other words, increase of contact conductance decreases the temperature difference between panel and equipment. There is highly dissipative equipment in S/C that uses radiator panels as a heat sink. Interface materials are needed in order to decrease the thermal resistance between these equipment and heatsinks.

Used interface materials at the STQM are;

- RTV 566,
- CV-2942,
- SIGRAFLEX

Performance of interface materials varies to the application and installation method. Former conductance measurement test shows performance variation of RTV 566. Even application of different torques with different operators also changes the performance of thermal interface material. Reasons of this variation are;

- Detaching during the application,
- Nonhomogeneous interface material thickness

Contact conductance of thermal interface filler is calculated from Equation 3.

$$G_L = \frac{Q_{Cond.}}{A_c \Delta T} \tag{3}$$

Parameters of Equation 3;

- $Q_{Cond.}$: Amount of conductively dissipated heat,
- G_L: Contact Conductance for thermal interface material,
- A_c: Contact Area,
- ΔT: Temperature difference between panel and equipment TRP.

As a result, of the calculations, two distinct ranges are defined for thermal material conductance values. These ranges are defined as below;

- Dry Contact: 250-400 W/m^{2}K
- Thermal Interface Materials (TIM): 750-1750 W/m^{2}K'dir.

Thermo-optical property of Radiator Areas:
In order to represent the flight model radiator (OSR), external sides of communication and service panels are painted with white paint. Emissivity of white paint is calculated from shroud and panel thermocouple temperatures. Equation 4 is used for white paint emissivity calculation.

$$Q = \varepsilon A_r F \sigma \left({T_R}^4 - {T_S}^4 \right) \tag{4}$$

- Q : Dissipated heat
- $\boldsymbol{\varepsilon}$: Emissivity
- $\boldsymbol{A_r}$: Radiator Area
- $\boldsymbol{F}$: View Factor
- $\boldsymbol{\sigma}$: Stefan-Boltzmann Constant $= 5.670 \times 10^{-8} \mathrm{W/m^2K^4}$
- $\boldsymbol{T_R}$: Temperature of white painted panel
- $\boldsymbol{T_S}$: Temperature of TVC Shroud

Emissivity values of white paints are obtained from hot and cold case iterations. Since the white paint emissivity affects the equipment temperature on both IDT 1/2 and IDT 4 cases, Equation 4 is solved for both cases iteratively.

MLI Effective Emissivity:
Radiative heat transfer takes place not only at satellite-space interface but also at internal equipment satellite interior interface. TCS engineers use Multi-Layer Insulation (MLI) blanket for insulation purposes among equipment, S/C and space.

Structure of MLI blanket provides radiative and conductive isolation from the space. Radiative heat transfer minimization by interposing as many enclosing reflective surfaces as possible is practical between the object being insulated and its surroundings. Conduction heat transfer is minimized by low-conductance spacers between the reflective surfaces. Polyester netting, silk netting, tissue glass, etc., are well known materials, which are used to minimize thermal contact between layers. The effective emissivity is often used for calculating conductance between MLI blankets and satellite panels. The effective emissivity value $\varepsilon_{\mathrm{eff}}$ includes both conduction and radiation effects of MLI. The effective emissivity is an experimentally calculated value and depends on the applications. For the existing correlation study effective emissivity values are thought to be a changeable parameter.
Doenecke developed an approach for effective emissivity calculation. He fit the curves on the foreign experimental data by least square method. Finally, equation 5 and 6 are obtained. The average temperature value of MLI ($\mathrm{T_m}$) can be calculated from Equation 5.

$$4T_m^3 = \frac{(T_h^4 - T_c^4)}{(T_h - T_c)} = (T_h^2 - T_c^2)\cdot(T_h - T_c) \tag{5}$$

- $\mathrm{T_h}$: Highest MLI Temperature
- $\mathrm{T_c}$: Lowest MLI Temperature

Effective emissivity values calculated from Doenecke approach are shown in Figure 3.

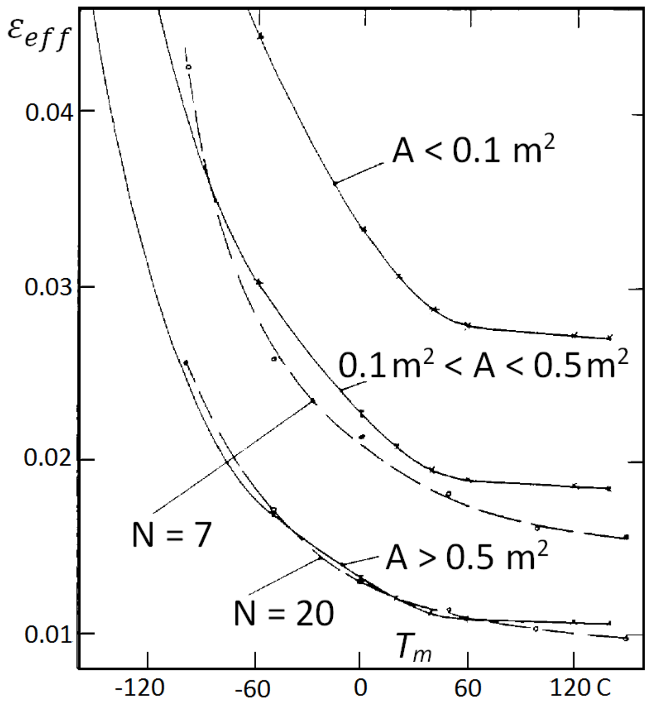

Figure 3: Variations of Effective emissivity as a function of Average Temperature ($\boldsymbol{T_m}$) [Doenecke, 1993]

Effective emissivity can be represented as a function of average temperature layer factor, area factor and perforation factor as in Equation 6.

$$\varepsilon_{eff} = \left(0.000136 \cdot \frac{1}{4\sigma {T_m}^2} + 0.000121 \cdot {T_m}^{0.667}\right) \cdot f_N \cdot f_A \cdot f_P \qquad (6)$$

- ε_{eff} : Effective emissivity Coefficient
- σ : Stefan-Boltzmann Constant $= 5.670 \times 10^{-8} \mathrm{W/m^2K^4}$
- T_m : Average Temperature
- f_N : Layer Factor (Depends of the Number of MLI Layer)
- f_A : Area Factor (Depends of the Area of the manufactured MLI piece)
- f_P : Perforation Factor

0.000136 ve 0.000121 coefficients are obtained from least square method. During the correlation study, analysis and test results show that effective emissivity values of panels are different.

Heater Resistance Effect:
All TCS heaters and some of equipment heaters are selected from CLAYBORN brand heater. The comparison of analysis and test results shows us that roll type heaters are not as effective enough as they are designed to be. TCS heaters are commonly not operational at the IDT 1/2, (which is the worst hot case simulation of satellite). However, they are ON at the IDT4 case (which is the worst cold case/safe mode simulation of satellite). It is understood from the test results that some portion of generated heat of TCS heaters are not conducted to the panel effectively.
Most of the TCS heaters are located on the communication panels. The conducted heat ratios of these heaters to the satellite are tabulated as in
Table 5. Tabulated ratios are found iteratively using the IDT 4 case results. Conducted heat ratio of TCS heaters directly affects the equipment temperature.

Table 5 TCS heaters conducted ratios

Panel	Conducted Heat Ratio of TCS Heaters (%)
North Com. Panel	45-65
South Com. Panel	43-54
North Service Panel	100
South Service panel	100
Star Trackers	50-75

Panel Transversal Conductance:

Thermal conductance values are used for axial heat transfer calculations through the panel. Because of the high thermal conductivity of aluminium, satellite panels are assumed to be longitudinally and laterally isentropic. At the very beginning of analyses (before correlation studies are preformed), the panel conductance values are calculated using datasheets of panel material. Cross-section of aluminium structural panels are given in Figure 4, including battery panels and service panel structures. Transversal conductivity (Z-direction) of panels is a combination of adhesive, honeycomb material and face skins resistances.
Test results demonstrate that north service equipment has higher temperatures than found from the TMM. Average test temperature of interior thermocouples of north service panel is found as 5.5 ˚C whereas average test temperature of exterior thermocouples of north service panel is found as 1.9 ˚C. Consequently, transversal conductance values of north service panel are decreased by %50 with respect to the datasheets calculations.

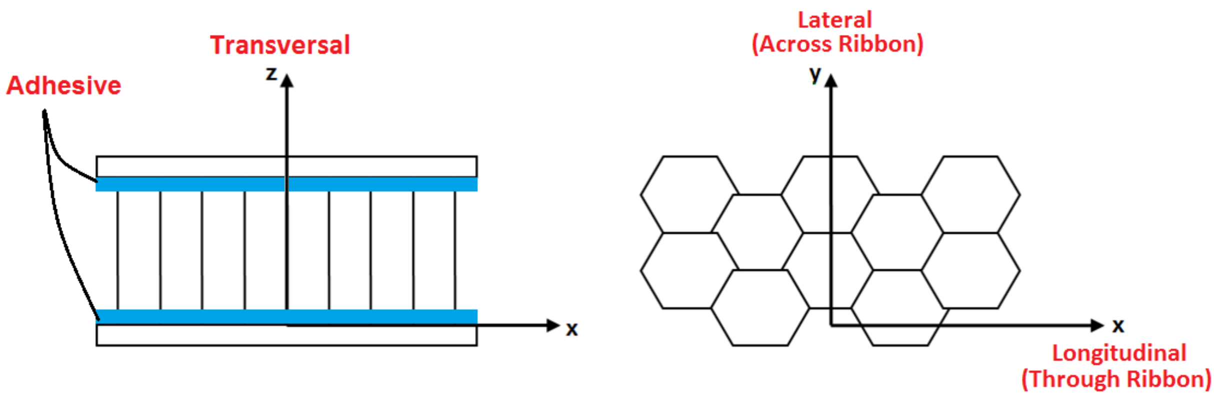

Figure 4: Cross Section of Battery Panels

Time Dependent (Equinox) Case Correlation:

IDT 3b is the only time dependent case, of STQM thermal tests, which simulates eclipse period of satellite in orbit (72 minutes). The main goals of correlation studies of this case are, evaluation of batteries' radiator areas, examining the adequacy of heater powers and accuracy of battery panel conductance and finding out the thermal capacitance value of batteries. Four thermocouples are located on batteries for temperature monitoring of each battery. Figure 5 represents battery temperature variations as a function of time.

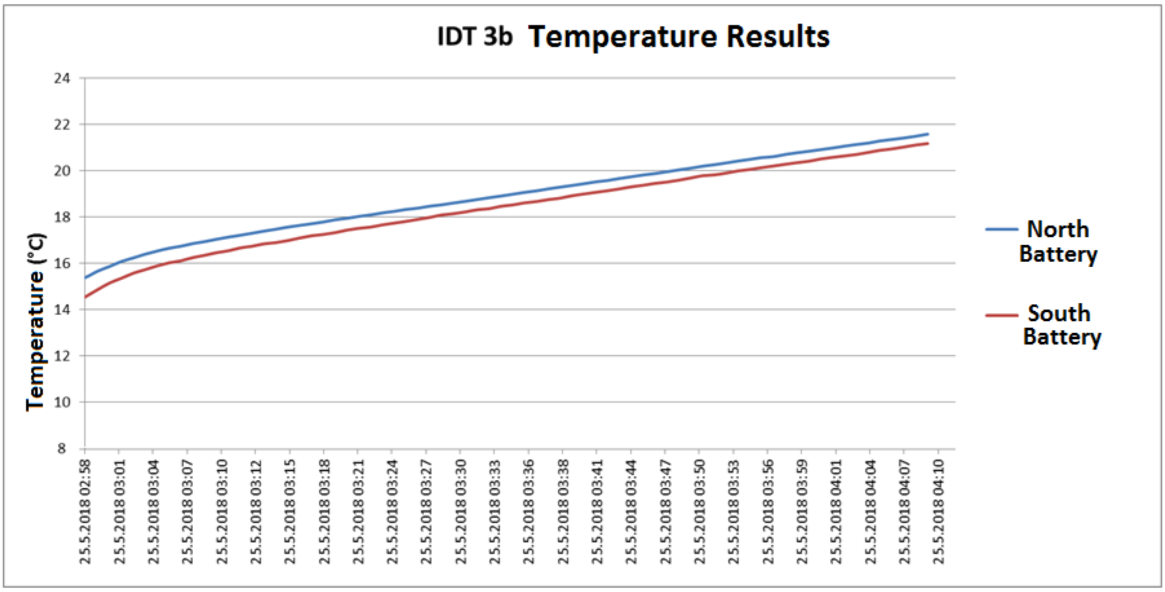

Figure 5: IDT 3b Case Temperature Results

During IDT 3b case, temperatures of batteries stay in the defined range (qualification limits). They do not exceed the upper operational temperature limit of battery, which is 35°C. Results proved that the current radiator area of batteries is enough for keeping temperature at the desired level.

It is also monitored that battery temperatures do not exceed the lower operational temperature limit, which is given as 0°C. This shows that the battery heaters are capable of keeping the battery above the required lower temperature limit.

In addition to these parameters, battery panel conductance is also examined. The contact conductance between panel and battery is correlated in the TMM. After that modification IDT1/2, IDT4 cases are solved again, and success criteria is checked.

CONCLUSION

In this study, two distinct thermal design cases of satellite, worst hot case and worst cold case are solved iteratively. Contact conductance of equipment, emissivity of radiators, MLI effective emissivity, heater power and panel transversal conductance parameters are checked. Success criteria is calculated after every parameter change and each equipment temperature is examined solely. Finally, thermal mathematical model is correlated and distribution of temperature differences for equipment are given in Figure 6 and Figure 7. Standard deviations are calculated for every iteration and final values are found out to be 1.83 for worst hot case (IDT 1/2) and 1.77 for worst cold case (IDT 4). These values show that second success criteria for the correlation is achieved.

During the correlation process of STQM TMM below success, criteria are aimed to be achieved.

- Mean Deviation Value **±2K**
- Standard Deviation Value **<3K, 1σ**
- Typical maximum deviation (taken uncertainty values at the thermal analyses); for STQM, 10K for internal equipment and 15K for external equipment.

Keeping dummy temperatures at the defined temperature levels show that the thermal design of the STQM is acceptable. Selected heaters, defined radiator areas, selected heat pipes and MLI covered areas are capable of thermal control for STQM. The correlation study for TMM of STQM is performed as planned. Available modifications will apply to the Engineering (Qualification) Model. In the thermal balance test campaign, components of passive thermal control hardware (conductance of interface material, effective emissivity of MLI, emissivity of radiator areas, heat transport capabilities of heat pipes) are verified. Since all electronic equipment are dummies and there are no thermistors to be read, thermocouples are used to control TCS heaters manually and TCS heaters' power values are shown to be enough from thermal design point of view. Given conductance values of embedded and surface mounted heat pipes are verified from comparison of test and TMM temperature differences. During the thermal balance test campaign, all design cases were performed and investigated. Adequacy of thermal hardware is tested with both substitutive and real equipment operation scenarios. Mean deviations and standard deviations of dummies for hot case (IDT 1/2) are given in Figure 6.

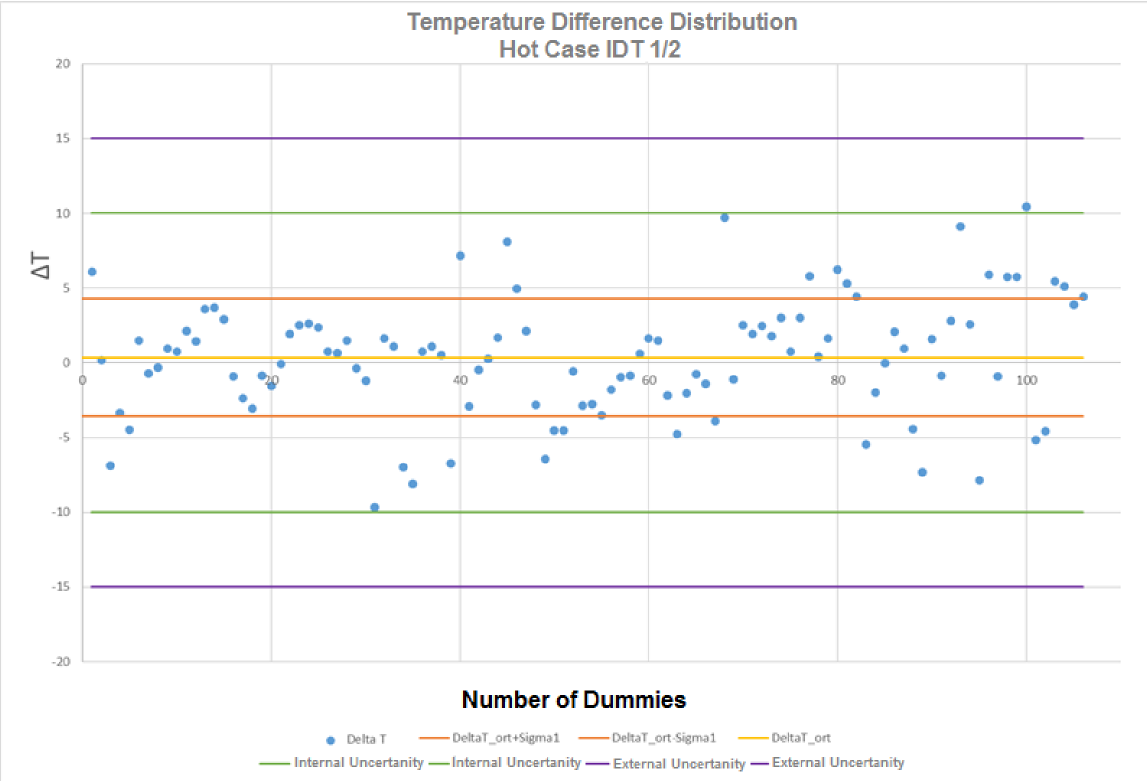

Figure 6: Hot Case Correlation Graph

Mean deviations and standard deviations of dummies for cold case (IDT 4) are given in Figure 7.

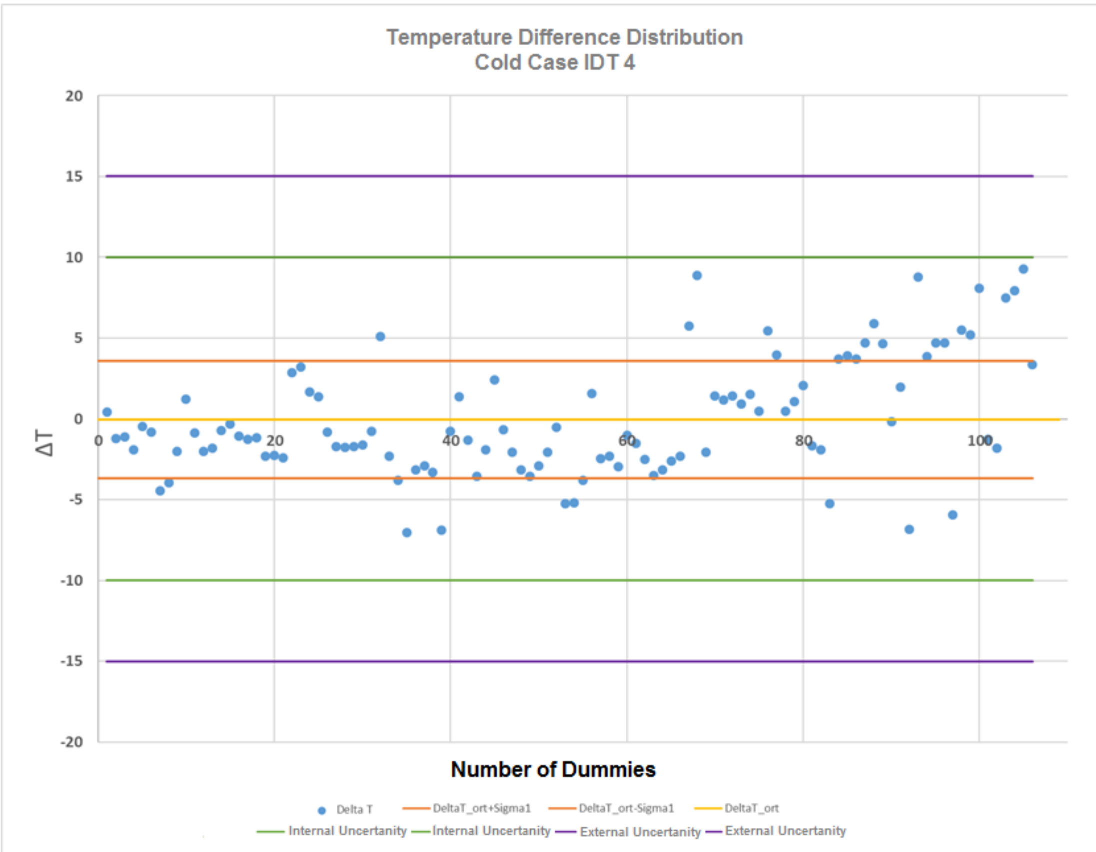

Figure 7: Cold Case Correlation Graph

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Figure 8: Photo of Thermal Team with STQM in TVC

References

ECSS-E-ST-31C Space Engineering Thermal Control General Requirements, ECSS Secretariat, (2008)

D. G. Gilmore, (2002) Spacecraft Thermal Control Handbook, Volume: 1 Fundamental Technologies, 2nd ed., The Aerospace Press, California, 2002

NASA, “Thermal Network Modeling Handbook” Reformatted by K&K Associates, Westminster, CO USA, (1999-2000)