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THERMAL DESIGN SOLUTION OF THE DNR EXPERIMENT FOR OPERATING ON BOARD THE INTERNATIONAL SPACE STATION

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Abstract. The paper describes the thermal solutions implemented during the design of the DRM experiment that was operated on board the International Space Station in 2006, during the 13th Centenary Mission. The thermal design of the experiment included the analysis of input requirements, choosing the thermal control concept, thermal modeling, implementation and validation by tests. To fit the rigorous time schedule, fast evaluation techniques and simplified mathematical models were used. The success of the modeling results validated by tests proves the correctness of the thermal design solutions applied for the experiment.

Keywords. *International Space Station, thermal control, thermal design, scientific experiment, anodizing.*

1. Introduction

The experiment described here is called DRM from **D**NA **R**epair under **M**icrogravity. It was operated on board the International Space Station in 2006, during the 13^{th} "Centenário" mission. The purpose of this experiment is to study the effect of ultraviolet in the DNA repair of the Escherichia coli bacterium in micro-gravity. The DRM experiment used ultra–violet UV-A 375 nm as irradiation source. For this purpose, UV-A Light Emitting Diode (LEDs) has been used in a hermetically closed cavity. After the irradiation on board the ISS, the biological material and the Memory Module were returned back to Earth where they were analyzed under laboratory conditions in Brazil. The experiment was developed in the State University of Rio de Janeiro (UERJ), in cooperation and with the engineering support provided by National Institute for Space Research (INPE), Brazil.

The DRM experiment consists of two different modules, the UV Irradiation Module and the Electronic Module. The maximal temperature in the sample wells of the biological material must not exceed 39 ^{o}C according to the survival requirements of the bacterium. Besides the particular specification, any experiment on board of the International Space Station should meet a set of general design requirements. The requirements for the equipment that will be transported, stored, accommodated and operated on the Russian Segment (RS) of the International Space Station (ISS) should be in line with SSP 41163 (ISS RS Specification) and the requirements of SSP 50094 (Consolidated RSA/NASA ISS RS Specifications and Standards Document). One of the most rigorous sets of requirements is about safety, mainly stated in SSP 50146, Bilateral RSA/NASA ISS Safety Assurance and Mission Requirements. All experiments and related documentation should go through a series of revisions before being allowed on board.

Especially, as mentioned in the thermal section of the safety requirements, the maximal temperature of external surfaces of experiment parts must not exceed the limit of 40°C in any ISS atmosphere condition. The specified parameters of ISS atmosphere were used as the input data for thermal design. By the specification, the temperature of gas atmosphere in the habitation area shall be from 18°C to 28°C; relative humidity shall be from 30% to 70%, and up to 95% for short duration (up to three hours per day); the dew point temperature shall be between 4.4°C and 15.6°C. Overall nominal pressure on the ISS shall be maintained in the range from 734 mm Hg to 770 mm Hg, minimum pressure shall be at least 700 mm Hg. The effective atmosphere velocity in the Russian Segment (RS) cabin aisle ways shall be maintained within the range of 0.05 to 0.20 meter per second.

In additional, the experiment should meet, as much as possible the general recommendations for the space equipment, particularly be limited for mass, volume and power consumption.

2. Experimen set up

The experiment consists of two different modules, the UV Irradiation Module and the Electronic Module. The flight configuration of the experiment, as it was installed on board the ISS RS, is shown in Fig. (1).

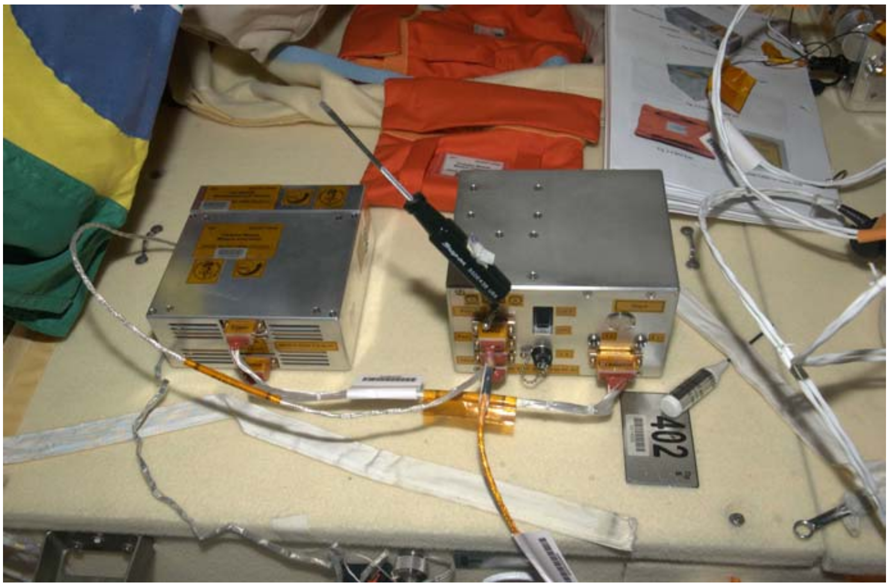

Figure 1. DRM experiment on board the ISS.

The Electronic Module (EM) is shown on the right side of Fig. (1), and the Irradiation Module (IM) is shown on the left side. The biological material is contained in the IM, whereas the EM provides the control and power supply to the IM. The base block of the IM is a solid plastic containing 4 one-milliliter sample wells, where the irradiation of biological material takes place, and four 25 micro-liters control wells, where no irradiation occurs. The near electronics consist of two circuit boards on top and bottom sides of the plastic block.

2. Thermal design solution for Irradiation Module

2.1. Development of the thermal test

For the Irradiation Module, the convective cooling using two fans (one redundant) was adopted.

Figure 2. Evaluation of the fan cooling efficiency for the IM main block.

Such a solution allows effective cooling of the irradiation cavity, near the electronics and the external box surfaces. This thermal design concept was chosen to meet the specific requirement of the maximal temperature limit of 39 ^{o}C for the survival of the bacteria. A simple experiment was performed to approve the adopted conception. The set-up is shown in Fig. (2). In the first phase of the test, the temperature curve was obtained for the conditions of natural convection to confirm the necessity of fan application. The test results for natural convection cooling are shown in Fig. (3). The T1 and T2 temperature sensors are positioned at the inner part of the IM, near the irradiated sample wells.

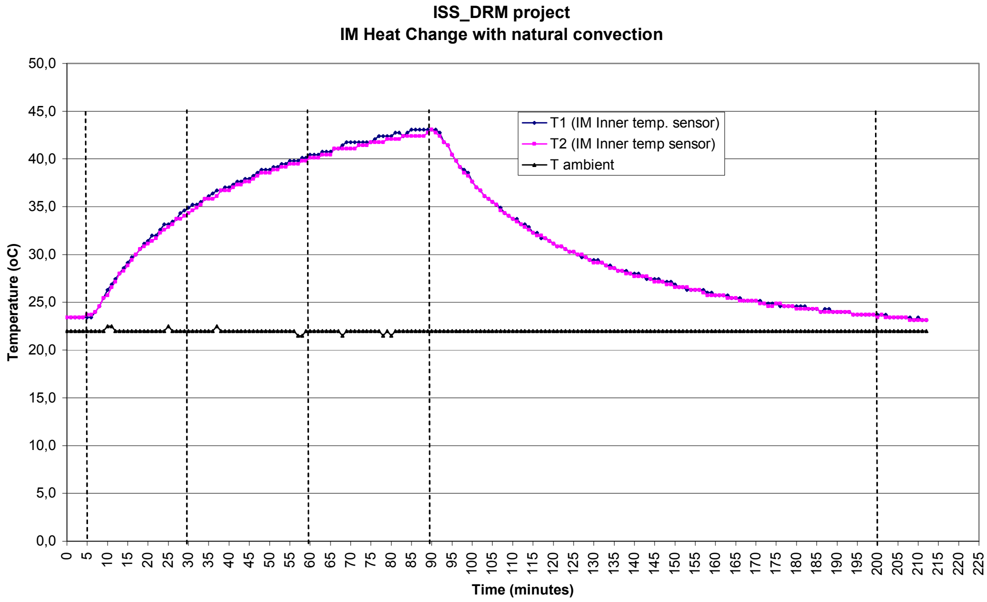

Figure 3. Natural convection cooling of the IM main block.

It is seen that about 50 minutes after switching on, the bacteria survival limit exceeded the temperature limit of 39 ^{o}C, even at comfortable ambient temperature level of about 22 ^{o}C.

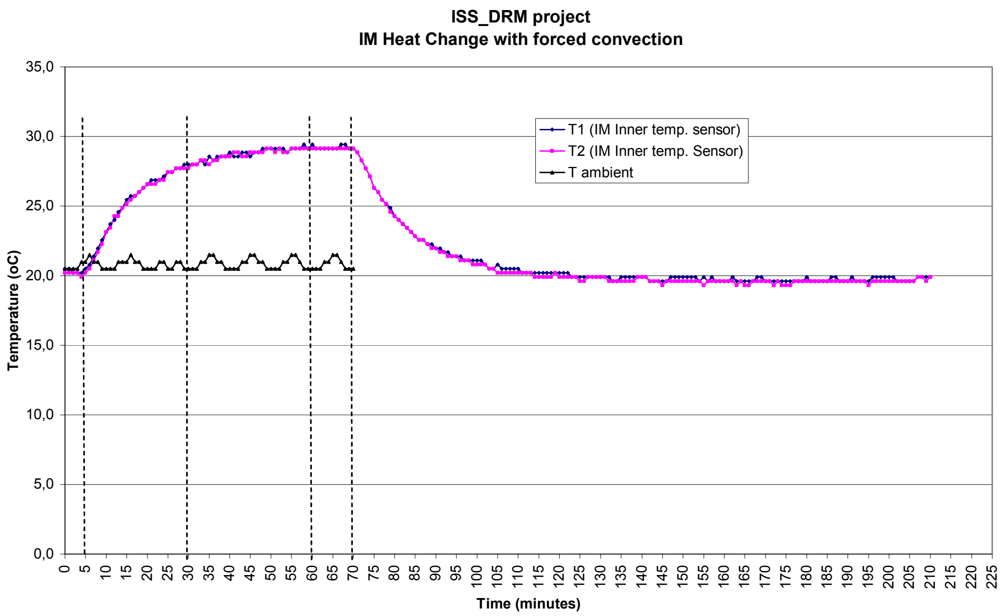

Figure 4. Forced convection cooling of the IM main block.

In the second phase of the test, the fan was switched-on. Figure (4) shows the temperature curve of the cooling improved by the fan using.

The first phase of test shows that under conditions of natural convection the temperature of the UV Irradiator Module may reach 19 ^{o}C above the ambient room temperature and keeps rising. Therefore, when the ISS indoor temperature is 28 ^{o}C, the IM temperature may reach the level of 47 ^{o}C which is quite unacceptable.

The second phase of the test demonstrates that, if fan cooling is applied, the temperature of the IM raises only 8 ^oC above the ambient temperature and then stabilizes. In this case, the maximum temperature in the vicinity of the sample wells may not exceed 36 ^oC, that is less than the limit of 39 ^oC, even when ISS atmosphere temperature is on its maximal allowable level of 28 ^oC. Therefore, the fan cooling must be used to provide required thermal control for the IM and the proper survival of the biological material.

2.2. Ambient test of flight model of the IM

In the final design of the IM, the cooling block, containing two equal fans were attached to the IM box; the assembling is shown in Fig. (5). The fans are of 60 mm ball bearing type, having 0.58 m3/min (20.7 CFM) of the nominal air volume flow rate and 1.92 W of the electric power consumption.

The IM flight model was submitted to ambient thermal test to evaluate maximal temperatures of the IM. The tests were executed in the laboratory ambient chamber with chamber ventilation switched-off. The position of the thermocouples for the measurement of the surface temperature is indicated in Fig. (5).

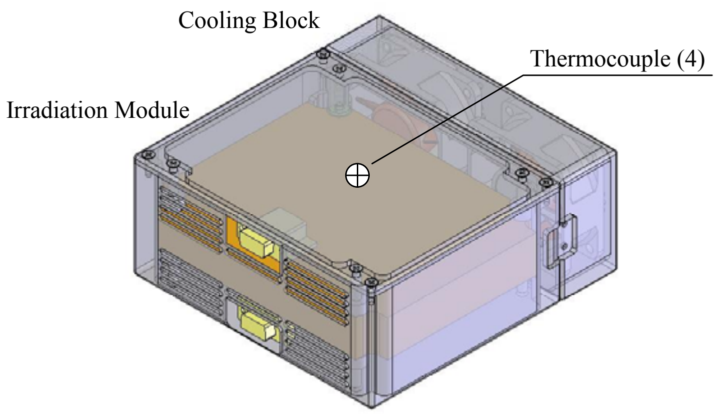

Figure 5. IM final design, and location of the thermocouples during the ground ambient test.

The test took about 5 hours to be performed. The measured temperatures are shown in Fig. (6).

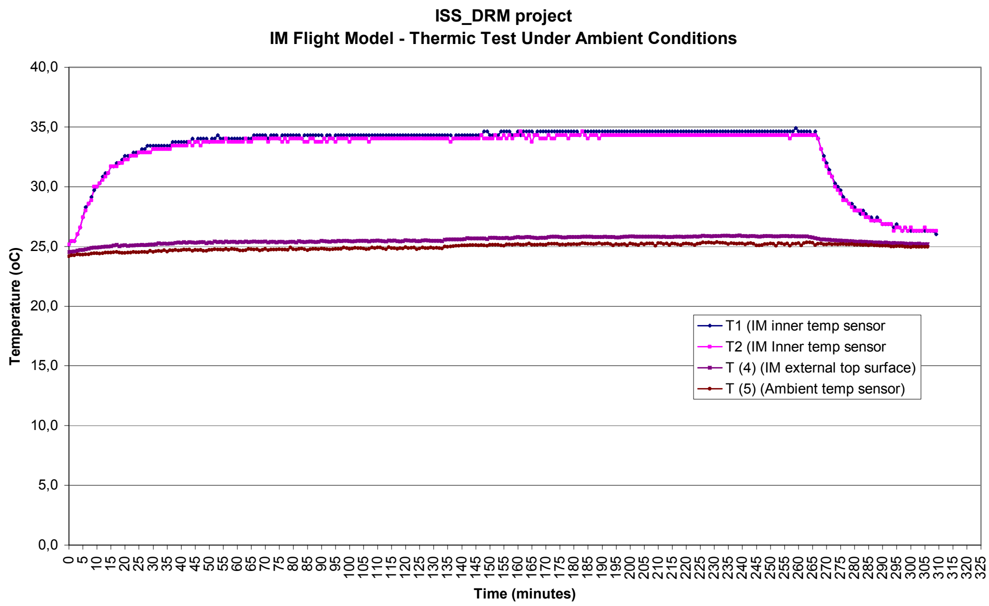

Figure 6. Results of ambient thermal test of the IM in its final configuration.

During the 4th hour of the experiment operating, when the steady condition was certainly reached, the following average values of temperature have been recorded, see Tab. (1).

Table 1. Measured and evaluated temperatures of the Irradiator Module

Description	Sensor	Test data	Predicted, under ISS cond-s
Internal temperature, oC	Internal thermistor T1	34.6	37.4
Internal temperature, oC	Internal thermistor T2	34.3	37.1
Surface temperature, oC	T-type thermocouple (4)	25.8	28.6
Ambient temperature, oC	T-type thermocouple (5)	25.2	28.0

The results above were obtained under ambient temperature of 25.2 ^{o}C with two working fans in the cooling block. The evaluation of on-board temperatures of the IM can be performed by shifting all temperatures to adjust the worst-hot ambient temperature of 28.0 C. The predicted temperatures are shown in the last column of the table 1. The difference between the internal IM temperature and the ambient one is 9.3 ^{o}C that is a little higher than for the case of fan cooling of single IM main block (8 ^{o}C). Thus, the assembling of the fan block into the IM and consequently narrowing of air flow passages gave only 9.3-8.0=1.3 ^{o}C increasing of the temperature difference above the ambient temperature. The maximal predicted internal temperature of IM, calculated as 37.4 C, is less that the established limit of 39 C. The maximal surface temperature of 28.6 C is well below the safety requirement of 40 C. Therefore, the conducted ambient test confirmed the IM design meets all thermal requirements.

3. Design thermal solution for the Electronic Module

3.1. No-fan thermal conception for the Electronic Module

For the Electronic Module, no-fan conception of thermal control has been chosen to simplify the design and reduce the electric power used. The aluminum case of the EM, anodized for high emissivity, was used as an in-cabin-radiator, relayed on the combined convective-radiative cooling. Most dissipated internal electronic components were mounted on the case wall from the internal side, having good thermal contact with the case wall surface. The EM design with opened top part of the case is given in Fig. (7), where the front panel (1), the base with electronic board (2) and the top case (3) are shown. The low-dissipated electronics were placed on the bottom-front panels, while the top "radiator" was loaded by the 5 most dissipated components: two DC/DC converters, two Voltage Regulators and one EMI Filter.

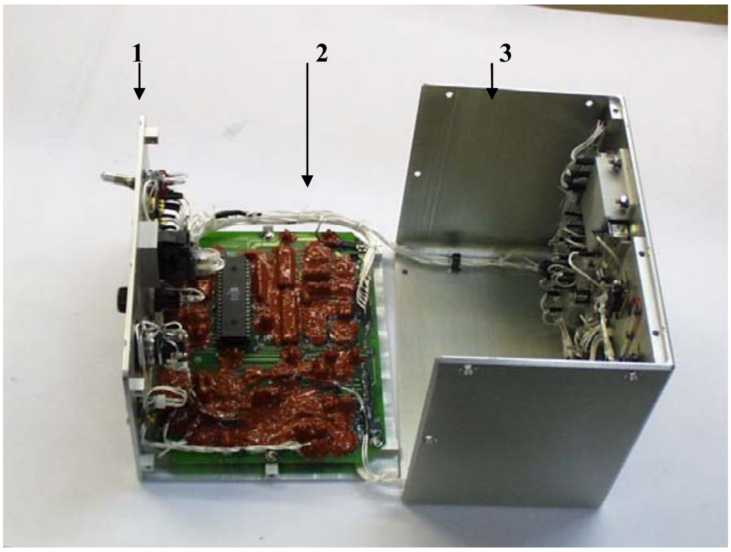

Figure 7. The EM final design with opened top plate.

To prove this conception of cooling, associated with thermal mathematical models for rapid thermal analysis were developed; they will be presented in the next section.

3.2. Transient thermal analysis

The simplified transient analysis is based on the transient energy balance, expressed by

$$Cm\frac{d\overline{T}_w}{dt} = Q(t) - (\overline{T}_w - T_{amb})\sum_{i=1}^{5} h_i A_i - \varepsilon\sigma(\overline{T}_w^4 - \overline{T}_{w,amb}^4)\sum_{i=1}^{5} A_i \quad (1)$$

Where $\overline{T}_w$ – is the volume-average temperature of the EM, ε_f – is the emissivity of the box external surface, h_i – is the convective heat transfer coefficients for each box side, envolved in heat transfer, and A_i – is area of I-th surface.

The following input data was used for the analysis: the ISS atmosphere temperature is 28 ^oC (hot case); velocity of air flow is 0.05 m/s (worst case); the ISS in-cabin wall temperature is 23 ^oC (average case).

The heat transfer coefficient for low-Reynolds forced convection flow was calculated by the relationship for the average Nusselt number over the surface area of heat transfer,

$$Nu_L = \frac{2}{9}\sqrt{\mathrm{Re}_L}\,\mathrm{Pr}^{1/3} \quad (2)$$

The temperatures in each 30 min after start-up from 28 ^oC (hot case) are demonstrated in Tab. (2), and the result temperature curve is shown in Fig. (8). The equation was solved using the Mathematical package (Wolfram, 1991).

Table 2. Simulated temperatures of the EM each 30 min after switch-on

t=	0	30 min	60 min	90 min	120 min
T_w=	28.0 C	36.3	37.7 C	38.0 C	38.4

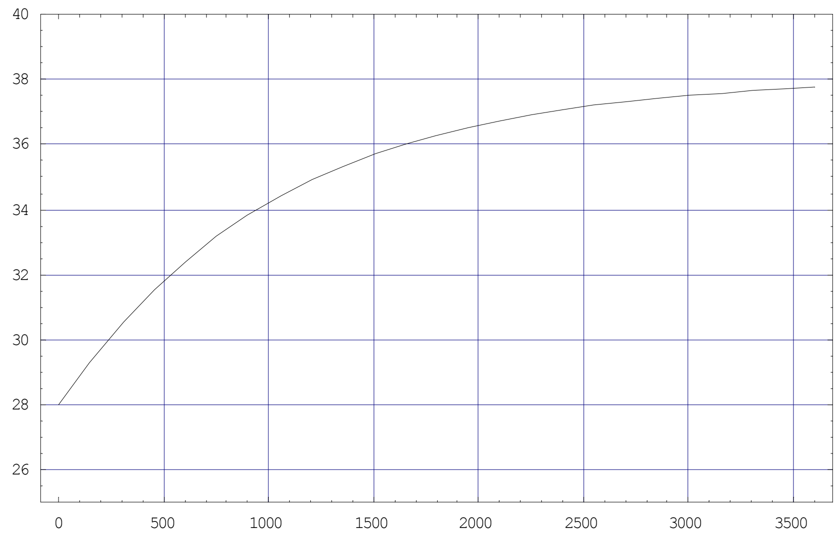

Figure 8. Simulation of the EM average temperature rise started from 28 ^oC (hot case, ^oC vs. sec).

The simulation shows the EM achieves its steady-state temperature of 38.4 ^oC after 115 min of operation under the predicted dissipating power of Q=7.1 W.

3.3. Analysis of temperature homogeneity

The evaluation of the temperature homogeneity is performed on the base of the analysis of temperature distribution over an equivalent rectangular plate having the same area, area-average thickness and area-average conductivity as the top part of the EM box (see Fig. (7), item 3). The plate is exposed to the combined radiative and convective heat transfer to ambient with the same parameters used for previous analysis.

The analysis is based on the solution of the 2D energy steady-state conservation, Eq. (3). To obtain the temperature map, the integral transform technique realized in a special tool was used (Vlassov, 1995).

$$k\delta\frac{\partial^2 T_w(x,y)}{\partial x^2}+k\delta\frac{\partial^2 T_w(x,y)}{\partial y^2}+q(x,y)-h_z(T_w(x,y)-T_{amb})-\varepsilon\sigma(T_w^4(x,y)-\overline{T}_{w,amb}^4)=0$$
$$\frac{\partial T_w(x,y)}{\partial n}\to 0 \quad \text{at edges} \tag{3}$$

The equivalent calculated dimensions of the equivalent plate are 292.2 x 268.6 mm; the equivalent thickness is 3.51 mm and equivalent thermal conductivity is 202 W/m/K. The dissipated elements for the present analysis, their heat rates and coordinates of the components corners are presented in Tab. (3).

Table 3. Characteristics of the most dissipating EM components

Component	Package	Q_{max} [W]	x1 [mm] (left)	x2 (right)	y1 (bottom)	y2 (top)	$T_{av\ brd}$, ^oC
DCDC1	MLWS612	2.61	84.6	121.6	110.3	139.3	39.0
DCDC2	MLWS612	0.95	84.6	121.6	79.3	108.3	38.7
Filter	MLWF200	0.09	84.6	138.6	156.3	185.3	38.9
Regul_5V	Reg 1	0.35	161.6	171.6	177.3	192.3	38.7
Regul_8V	Reg 2	2.88	197.6	217.6	167.3	192.3	39.3

The right column contains the predicted temperatures in the locals where the most dissipating components are placed. The predicted temperature distribution over the equivalent plate is shown in Fig. (9). The results were adjusted to keep the level of 38.4 ^oC, obtained from the previous analysis, as the average temperature of the equivalent plate.

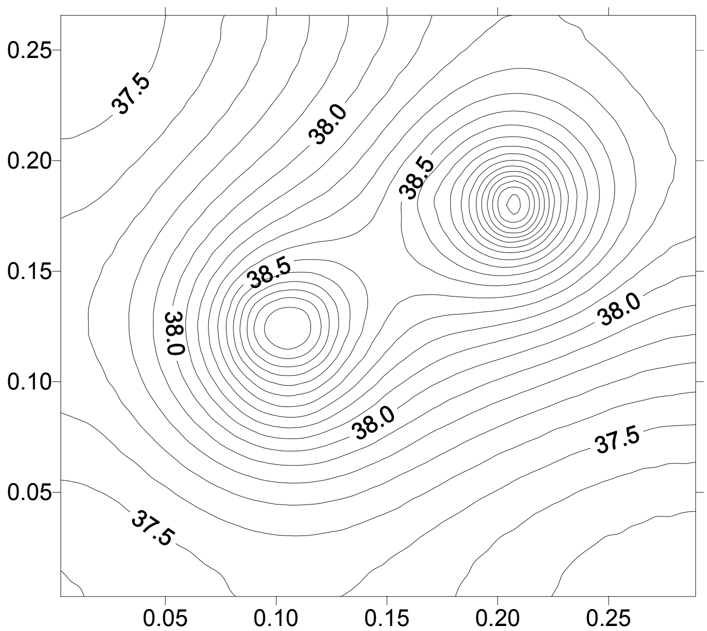

Figure 9. Temperature distribution over the equivalent plate

The results show that the maximal temperature in the hottest spot is T_{wmax}=39.7 ^oC . Therefore, the maximal temperature, taking into account the in-homogeneity, at worst hot case at steady-state conditions can reach T_{wmax}=39.7 ^oC, that is slight less than the limit of 40 ^oC. The temperature rising above the average plate temperature is ΔT=39.7-38.4=1.3 ^oC. The given temperatures were obtained under the supposition, that the external surfaces of the EM box is cured to reach the emissivity of at least ε = 0.82.

3.4. Result recommendations for Electronic Module design

On the base of present thermal analysis, the following thermal requirements to the EM thermal design have been elaborated

- Anodizing of all surfaces of the box wall to achieve the emissivity better than 0.82.
- As much as possible, the EM box wall should be machined from the solid piece of Al alloy having thermal conductivity not less than 167 W/m/C: such as Al 6063 T6; Al 6061 T6; -T8; -T9.

- Provide good thermal contact between box walls.
- Thickness of wall should be not less than 2.5...3 mm
- Increase thickness of wall under most dissipated components up to 5 mm.
- If total heat dissipation in the EM will exceed 8 W, the fan cooling is needed.

These recommendations have been accepted and implemented for the EM design.

3.5. Emissivity measurement of anodizing surfaces

To select the best type of the surface processing for the EM box, several exemplars of small plates (25.4x30mm) made from two aluminum alloys have been submitted to the technology tests. Different types of anodizing were applied, see Tab. (4). The anodizing process used here, follow the military standard MIL–C–81706, (1970) and European standard ESA PSS-01-703, (1982). The emissivity was measured for each plate with IR reflectometer DB 100.

Table 4. Characteristics of different types of anodizing

Al alloy	Photo	Technology process	Emissivity, average	Variations
6061 T651		Hard sulfuric anodizing without sealing (Sulfúrica DURA sem selagem)	0.84	±0.03
6061 T651		Conventional sulfuric anodizing with aniline sealing (Sulfúrica Convencional selado com Anelina)	0.84	±0.03
6061 T651		Chrome anodizing (Crômica)	0.72	±0.05
2024 T351		Conventional sulfuric anodizing with Nickel acetate sealing (Sulfúrica Convencional selado com Acetato de Níquel)	0.89	±0.01
2024 T351		Conventional sulfuric anodizing with aniline sealing. (Sulfúrica Convencional selado com Anelina)	0.89	±0.01
2024 T351		Chrome anodizing (Crômica)	0.73	±0.07

By the IR measurement results, the best anodizing process for Al 2024 alloy, selected as the EM box material, is conventional sulfuric anodizing with Nickel acetate sealing; it provides the 0.89 emissivity. The other convincing reason to choose this anodizing technique is that it uses an inorganic dye as sealing, eliminating therefore any undesirable gas emission (off-gassing) for the confined ISS environment.

After the treatment, the EM box was submitted again to the IR test. Surprisingly, the test showed much lower average emissivity $\varepsilon = 0.83 \pm 0.01$. Nevertheless, the EM box surface anodizing treatment was accepted because the emissivity obtained still met the thermal design requirement.

3.6. Ambient test of flight model of IR

Ambient thermal test was performed to evaluate maximal temperature on the surface of the electronic module under conditions of the natural convection cooling. The natural convection represents more closely the conditions of ISS atmosphere when airflow velocity is minimal (0.05 m/s, worst case). The obtained results are using also to validate the thermal mathematical model of the EM. The positions of three T-type thermocouples on the EM are shown in Fig. (10).

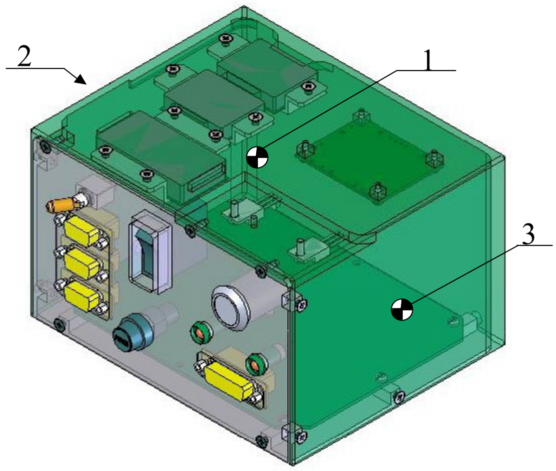

Figure 10. Positions of thermocouples on the EM ambient test.

The test was performed in 5 hours; the result temperature curves are displayed in Fig. (11).

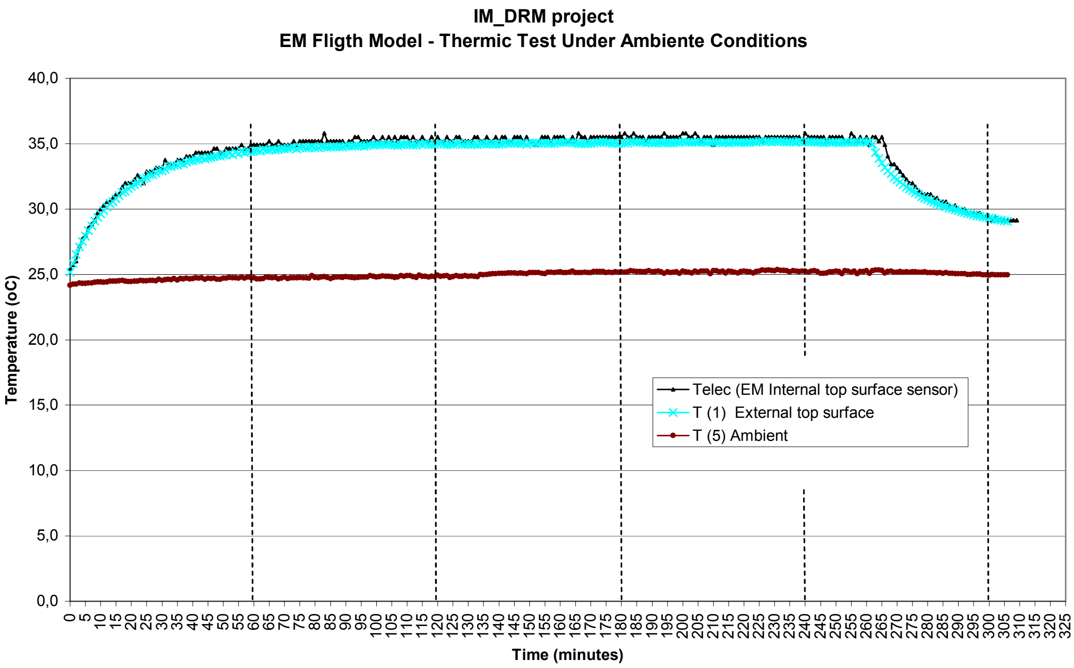

Figure 11. Results of ambient thermal test of the EM in its flight configuration.

During the 4th hour of the experiment running, when the steady condition was surely reached, the following average values were recorded, see Tab. (5).

Table 5. Measured temperatures of Electronic Module

Surface temperature, °C	T1	35.1
Surface temperature, °C	T2	33.9
Surface temperature, °C	T3	33.9
Average temperature, °C	$T_{av}=(T_{min}+T_{max})/2$	34.5
In-homogeneity, °C	$\Delta T=T_{max}-T_{min}$	1.2
Ambient temperature, °C	T_{amb}	25.2

3.7. Validation of the mathematical model and formerly obtained results

The conditions of the actual ambient tests, where natural convection is essential, are different of those in ISS habitual compartment. To validate the mathematical model, used for the design thermal analysis, the ground test conditions should be inserted in the model.

Heat transfer coefficient for natural convection is defined through known criteria relationship. In the case of the rectangular plate, cooling from above (this is the top surface of the EM), for laminar natural convection (10^4<Gr Pr<10^9), the Nusselt number is expressed through the following relationship (Isachenko et. al., 2000)

$$Nu_L = 0.54(Gr\,\mathrm{Pr})^{0.25} \tag{4}$$

For vertical lateral surfaces, where the heat transfer is more intensive, the factor changes from 0.54 to 0.59. Expected value of the Rayleigh number (Ra) is 0.6...1.3 10^6, thus the flow is laminar. The Grashoff number is defined keeping the length as a characteristic dimension

$$Gr = \frac{\rho_{ar}^2 g(T_w - T_{amb})L^3}{T_w \mu_{ar}^2} \tag{5}$$

Using these correlations, the simulation was performed for the ambient test conditions. The result temperature curves are shown in Fig. 12.

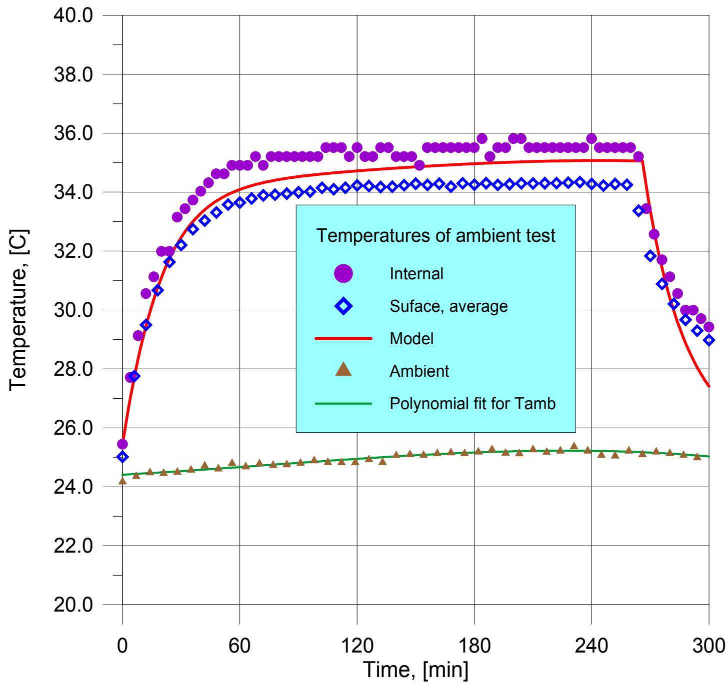

Figure 12. Measured and predicted temperatures of EM during ambient test

After achieving of steady state, the average surface temperature was obtained Tav=35.07 °C by the model, whereas the test gave 34.5 °C. Therefore, the difference for average temperature between test and the model is ~0.6 °C. This magnitude has been accepted as a precision of the thermal mathematical model of the EM. The mathematical model yields a conservative evaluation of average surface temperature, because the cooling effect through the bottom was not considered in the model.

To evaluate the precision of temperature field in-homogeneity prediction, the model of temperature distribution was run again with adjustment of the average temperature to measured value of 34.5 ^oC. The results of modeling and temperatures measured in the same points are summarized in Tab. (6).

Table 6. Measured and predicted temperature over the surface

Description	Denomination	Test data	By the model
Surface temperature, ^oC	T1	35.1	35.0
Surface temperature, ^oC	T2	33.9	34.3
Surface temperature, ^oC	T3	33.9	34.5
Temperature difference	T_{max}-T_{min}	1.2	0.7

As it seen from Tab. (6), the model gives more optimistic values in the term of homogeneity. Therefore, the difference of 1.2/2-0.7/2≈0.3^{o}C should be added to the predicted theoretical values of increasing over surface average temperature. Therefore, considering the test result, the temperature increasing of ΔT=1.3+0.3 = 1.6 ^oC should be added over the average surface temperature to evaluate the maximum temperature.

From another hand, the model gives 0.6 ^oC of conservatism to the average surface temperature, as it stated before. Therefore, to evaluate correctly the maximal temperature of the EM surface, the difference of the 1.6-0.6=1.0 ^oC should be added to the average temperature, predicted by the model. In our case this is 38.4+1.0=39.4 ^oC.

Therefore, the predicted maximal temperature of the EM surfaces considering area-inhomogeneity by the model adjusted by the ambient test is 39.4 ^oC that is less than the limit of 40 ^oC for the hot-case condition.

4. In flight temperature measurement and comparison with model

During the experiment conducted on board the International Space Station, the temperatures of both DRM modules were measured. The final curves are shown in Fig. (13).

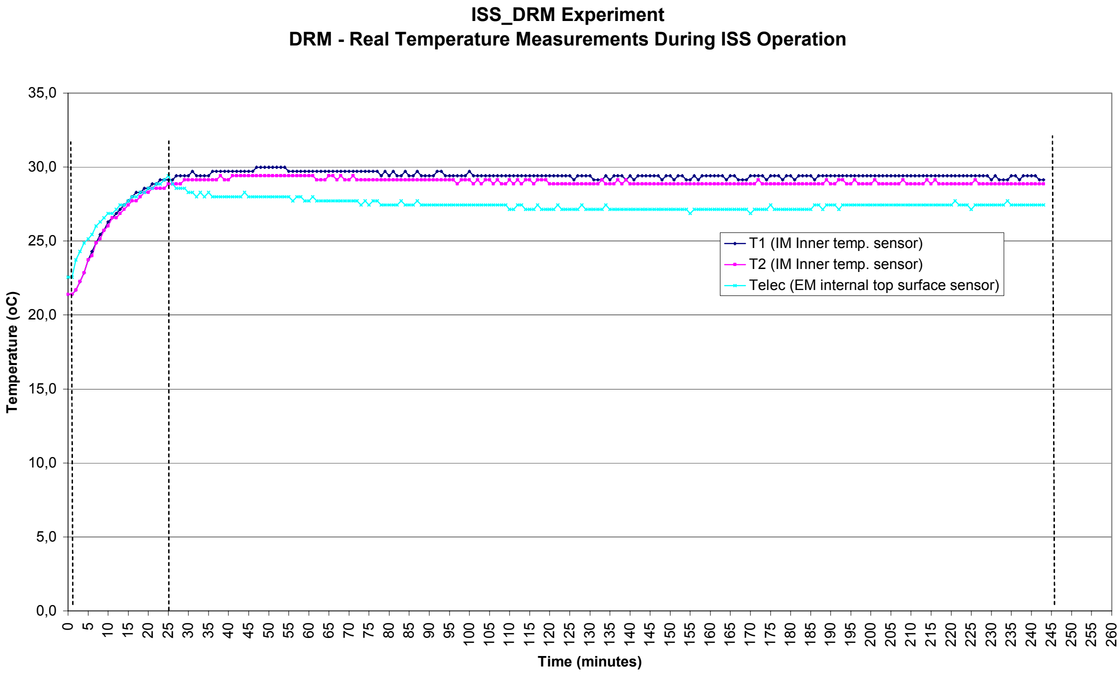

Figure 13. Temperatures of the DRM experiment, measured during operation on ISS

The experiment was operated in continuing mode during ~4 hours. It can be seen from the graph in Fig. (13), the IM temperature, after reaching the thermal steady state mode, was kept on level 29.7 ^oC with the initial temperature 21.4 ^oC, which is accepted as ISS atmosphere temperature in the experiment zone. Therefore the measured temperature difference above the ambient ISS air temperature was 8.3 ^oC, while the by the ground test the predicted value was 9.3 ^oC. The difference of about 1 ^oC may be explained by the contribution on the IM cooling of the external forced convection from ISS in-cabin ventilation, that was not included in the ground test.

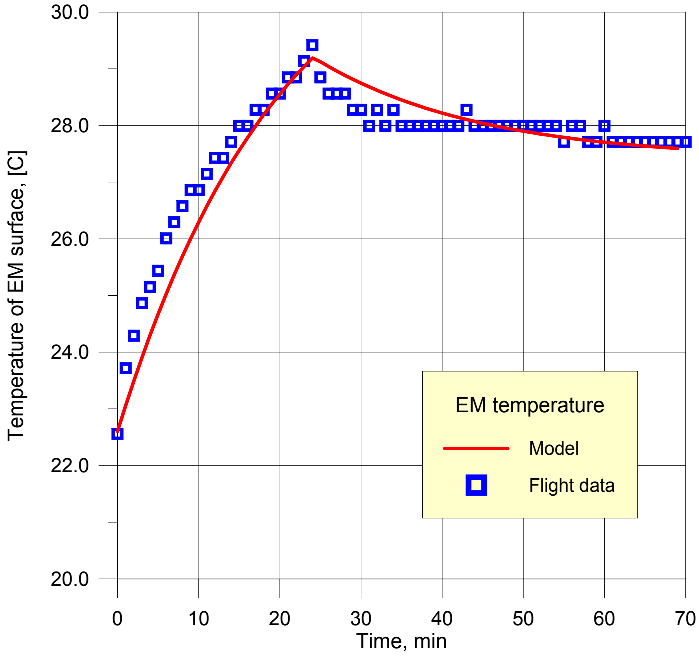

Figure 14. Temperatures of the EM during first 70 minutes of operating on ISS, measured and simulated

For EM, after first 25 minute of experiment, an event occurred: the power of 2 from 4 sets of irradiation leds failed. The reason is still under disclosing, but probably some electric impulse entered through the on-board power supply line and burned-out 2 transistors simultaneously . Thus, the EM dissipated power reduced from 7.6 W to 4.0 W. At t=25 min, the measured temperature of the EM reached 29.4 ^{o}C.

These conditions of the initial normal operating and subsequent partial failure and sudden dissipation change were reproduced in the thermal mathematical model. The real EM dissipated power also higher than predicted, 7.6 W instead 7.1 W; this new value was also inserted into the model. The results of modeling are shown in Fig. (14), plotted together with measured values. The heat transfer coefficient was adjusted to fits the experimental curve. Its value was 4.6 W/K/m^2, which can correspond the airflow velocity of about 1.1 m/s. Indeed, the DRM experiment was placed in a well-cooled place near the outlet of air-condition duct, where the conditions were far from worst case with its ventilation velocity of 0.05 m/s.

Finally, for the EM thermal model, the dis-accordance with experimental varies within –0.7 to +1.0 ^{o}C, that is considered as a very good achievement for the present thermal design.

5. Acknowledgement

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6. Conclusion

The paper confirms that even simple thermal mathematical models developed and applied correctly can serve as a useful tool along the ISS experiment design process to support the thermal design solutions. For the DRM experiment, development thermal models helped on the choosing the thermal control conception for the EM and IM, the prediction of maximal temperatures for operational and failure modes, proving the maximal surface temperature for rigorous safety review process. The model for the EM was validated by ambient tests by reproduction in the model the conditions of natural convection. The evaluated precision was within 0.6 ^{o}C of that is considered as a very good achievement. Flight measurement shows that with fitted coefficient of convective heat transfer, the dis-accordance between experimental and theoretical data varies within –0.7 to +1.0 ^{o}C that is also a very good result. Based on the modeling, a different thermal conception has been proved for the EM module, yielding simplified mechanical and more reliable design. Instead the traditional fan cooling, the anodized case was used as extended surface for mixed convection and radiation heat transfer.

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