EVOLUTION OF AN IDEA TO A SOLUTION: DEVELOPMENT OF THERMAL MANAGEMENT SYSTEM FOR AN EO PAYLOAD

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ABSTRACT

Thermal management system is essential for efficient operation of Electro-optic payloads in UAVs as the optimal performance of many Electro-optic sensors(EO sensors) is assured only within a certain temperature range. Also, lower temperatures can induce condensation which causes image quality to deteriorate. The main motive of the design and optimisation of Thermal management system(TMS) is to maintain the temperature of the turret within the required temperature, thereby guaranteeing the performance of the optical sensors. TMS helps to ensure that the imaging device outputs a clear image, as it helps to compensate for the change in temperature of the environment. TMS consists of cooling or/and heating systems with the necessary controls, fans, heaters, thermostats and relays. Arriving at the configuration of these system within the constraints of power, volume and weight and to meet the requirement is a journey by itself from ideation to experimentation and testing.

KEYWORDS

Electro-optic payload, UAV, MREO, ROC, IRA, thermostat, dew point temperature, thermal management, purging, etc.

1. INTRODUCTION

EO payloads helps in reconnaissance & surveillance, tracking and ranging in Unmanned Aerial Vehicles(UAVs) in all-weather and flight conditions. This requires a package of EO sensors like Day Television(DTV) camera, Infrared imager and LASER designators cum rangers etc. These sensors can be effective in the coverage and performance only if they are placed in a turret which helps to isolate them from the external environment like aerodynamic disturbances, structural vibrations and extreme temperature & humidity conditions. The turrets are normally designed as gimballed mechanisms with sealing & pressurization to cater to these requirements.

As the UAVs climb to higher altitudes, the temperature drops and the turret gets exposed to lower temperatures. Turrets for EO-payloads are sealed and pressurized to restrict the inflow of moisture. But at low temperatures, the limited amount of moisture in the turret can condense on the optical windows of the turret and the EO-sensors, thus adversely affecting the imaging.

Thermal management system plays this pivotal role of managing the heat within the system by adding heat into the system or by dissipating heat from the system. These systems are configured around designing and implementing techniques that leverage conduction, convection and radiation. The thermal management system being discussed in the present study is configured around thermostat and resistive electric heaters.

MREO stabilized turret is a medium range electro-optic(MREO) payload being designed for a UAV platform. The turret has a two axis four gimbal configuration with EO sensors located in the optical module which is a nearly spherical volume with optical windows for external viewing as shown in Figure 1.

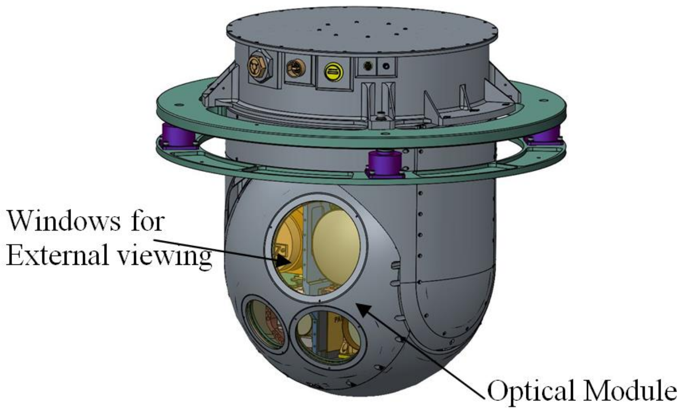

Figure 1: MREO stabilized turret

The UAV platforms can fly at altitudes close to 10km where the temperature can drop to -40ºC while it can be subjected to temperature as high as +55ºC while taking off. The EO sensors housed within the system has operating temperature limitations, at both extreme conditions. The operating temperature limitations of the sensors housed in the turret are as given in **Error! Reference source not found.**.

Table 1: Electro-Optic sensors mounted inside the turret

Sl .No.	Sensor	Operating Temperature
1	EO-sensor 1	-20ºC to + 60ºC
2	EO-sensor 2	-30ºC to + 70ºC
3	EO-sensor 3	-30ºC to + 65ºC

The minimum temperature that can be sustained by EO-sensor 1 is only -20ºC. Also, the condensation at low temperatures can degrade imaging performance of the system while flying at high altitudes. For relative humidity of 40%, 20% and 10% at 25ºC, the dew point temperatures are respectively 10.48ºC, 0.49ºC and –8.73ºC. Also, for dew point temperature to be below –10ºC, the relative humidity at a temperature of 25ºC should be below 9.05%. However, humidity indicator plugs that can read below 20% RH are not readily available off the shelf. Moreover, maintaining such a low humidity level will require large amount of desiccant and more frequent purging operations. Based on these considerations, thermal management system to be designed to operate and restrict the minimum temperature inside the turret above 10ºC.

MREO turret is sealed and pressurized with nitrogen. Nitrogen being a bad conductor of heat, the heat dissipation from EO sensors may result in hotspots. Also, the metal-to-metal contact of the components especially at gimbal joints are localised to the bearings. The surface area of the dome may prove to be beneficial for dissipating heat through convection to ambient. Hence the heat dissipation mechanism being considered in this system is restricted to circulation of heat by fans placed inside turret.

The objectives of thermal management system is hence to heat the volume when the temperature drops less than 10°C. Also the elements of TMS can be used to circulate the air with in the volume during the operation which is beneficial through out the operating temperature range.

2. CONFIGURATION DESIGN(IDEATION)

Thermal management system(TMS) shall consists of elements required for air circulation, heating and controls to ensure that the temperature inside the turret does not exceed the operating temperature limitation of the system. This need to be achieved within the volume, weight and power constraints meeting the certification requirements necessary for any airborne system. Further inputs that helped evolve a meaningful configuration are discussed as follows:

- On examining the turret, there are pockets of volume available between the EO-sensors and external housings which can possibly accommodate the elements required to form the thermal management system.
- Placement of heaters on the external housing may lead to higher loss of heat to external environment.
- Placement of fans on external housing may cause circulating air to hit directly on the EO sensors thus disturbing the field of vision.

These factors lead the configuration design to culminate in a fan-heater module consisting of axial/ventilator fan and cartridge heaters. Again, the heater carrying bracket is designed with unique features that made it modular and stackable. This gives the flexibility of adding heating power as assessed during the experiments.

Table 2: Specifications of fans

Sl No	Description	Specification
1)	Temperature range	Operating:-40°C to +70°C Storage: -55°C to +55°C
2)	Weight of fan	<0.5 kg
3)	Volumetric Flow rate at exit	>36m^3/hr
4)	Rpm of fan	>26000 rpm
5)	Dimension of the Impeller Casing	φ50mm x 40.5mm

Two numbers of axial fans (impeller units) are placed in the optical module. The placement of the fans are arrived based on the availability of space allowing for the degree of freedom of the gimbal. The controller boxes for the fan are separately placed in the spherical dome of the optical module. Based on the initial estimates, heat dissipation required inside optical module is around 800W(Q) for effecting a temperature rise of 54°C(ΔT). This can be divided among two modules. So considering 400w, the required mass flow rate in fan is calculated as Q/(Cp*Rho*ΔT) which is approximately 27.5m^3/hr. The specifications of the fan selected are as provided in Table 2.

The maximum heating requirement is 800 W. The supply from aircraft is 28V. The resistance of a 2inch x 2inch polyimide patch heater is 78.4Ohms which will hence provide heat of 282/78.4 = 10W. This implies placement of 73 patch heaters which requires a large surface area and hence may not be feasible. Usage of free Nichrome wires are also not considered as there is chance of wire getting cut during the operation of fan. High Watt density cartridge are identified as a suitable solution for MREO GPA Mk V due to the compact size and reliability since the nichrome wires are well protected inside the sheath. The nichrome wire never comes in contact with sheath due to the insulation in between. The specifications of the heater is given in **Error! Reference source not found.**. Four numbers of such heaters placed in front of each fan can assure the supply of 800W heating to the system.

Table 3: Specifications of high density cartridge heaters

Sl No	Description	Specification
1)	Watt Rating	100W
2)	Voltage	28VDC
3)	Length	40mm
4)	Diameter	8mm
5)	Sheath material	Stainless steel
6)	Resistance wire	High grade nickel chromium resistance wire
7)	Insulation	MgO

The axial fan-heater module realized is as shown in

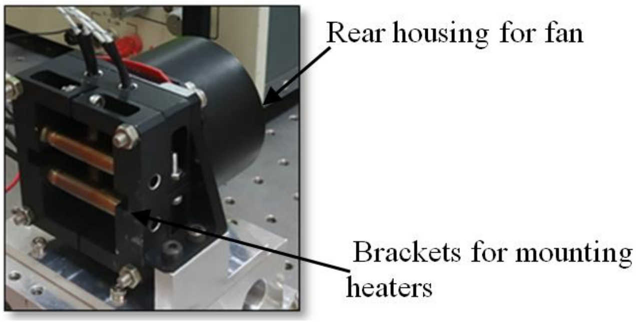

Figure 2. The fan is placed in the rear housing. It pushes the air through the brackets on which heaters are mounted.

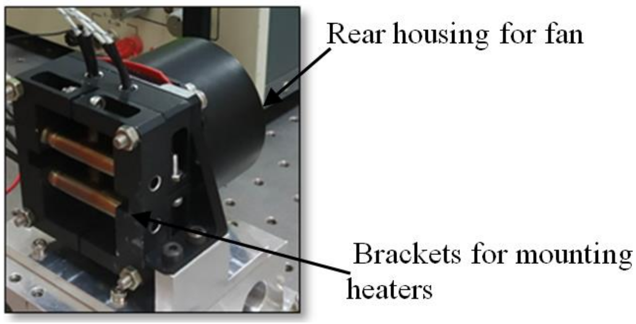

Figure 2: Axial fan- heater module

The next move is to experiment and collect data for the solution. This also aids in building up CFD models which can play a major role for any future modifications. Assembling a gimballed turret for this exercise is not practical as the EO sensors are costly and also, turret may require extensive rework to accommodate design iterations. This lead to the evolution of an experimental set up.

3. Development of the Test Set-Up

The gimballed turret of Medium Range Electro-Optic Sensors(MREO) consists of 3 EO-sensors with an inertial sensor placed in a spherical dome of 450mm diameter. The zone of interest for the TMS is the optical module. A test setup as shown in *Figure 3* is designed to simulate the flow and heat dissipation in the optical module during the operation of TMS.

The main objectives of the test set-up is to create the flow and heat dissipation as close to the real system. Dummy EO sensors with close similarity to the external shape of real sensors are designed and fabricated. Patch heaters are placed on the dummy EO-sensors, at the locations where the real unit is found to dissipate the heat. A total of 18 patch heaters of 10W and 8 numbers of 5W patch heaters are pasted to the different units placed in the TMS-test setup.

The spherical dome shape is also manufactured with close similarity to the real domes. Two fan-heater modules are placed on the payload plate, one in front and one in rear.

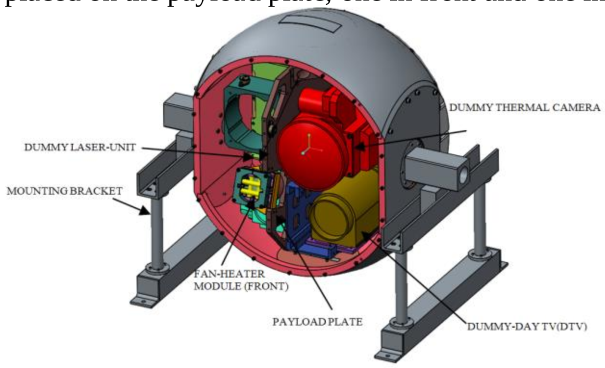

Figure 3: Experimental test set-up for thermal management system

The experimental test set-up is realized and the images are as shown in *Figure 4*. Total of 15 Resistance Temperature Detectors(RTD) sensors are placed around the units to monitor and capture the temperature inside the dome. The distribution of the RTDs inside the test set-up is as provided in Table 4. The schematics of power supply and sensors in the test set-up is shown in Figure 5, in which PS represents power supply and TS represents temperature sensor.

Figure 4: Images of TMS test -setup

Table 4 RTD sensor distribution in TMS test set-up

Thermal sensor	Location	Thermal sensor	Location
TS 1	Front dome	TS 9	Between LASER units
TS 2	Back dome	TS 10	Inner surface of front dome
TS 3	Ambient	TS 11	Payload plate-top
TS 4	Thermal camera surface	TS 12	Payload plate-front
TS 5	DTV	TS 13	On LASER units
TS 6	LASER unit surface	TS 14	Inner surface of back dome
TS 7	Payload plate-near FLIR	TS 15	On thermal camera window
TS 8	Payload plate-bottom		

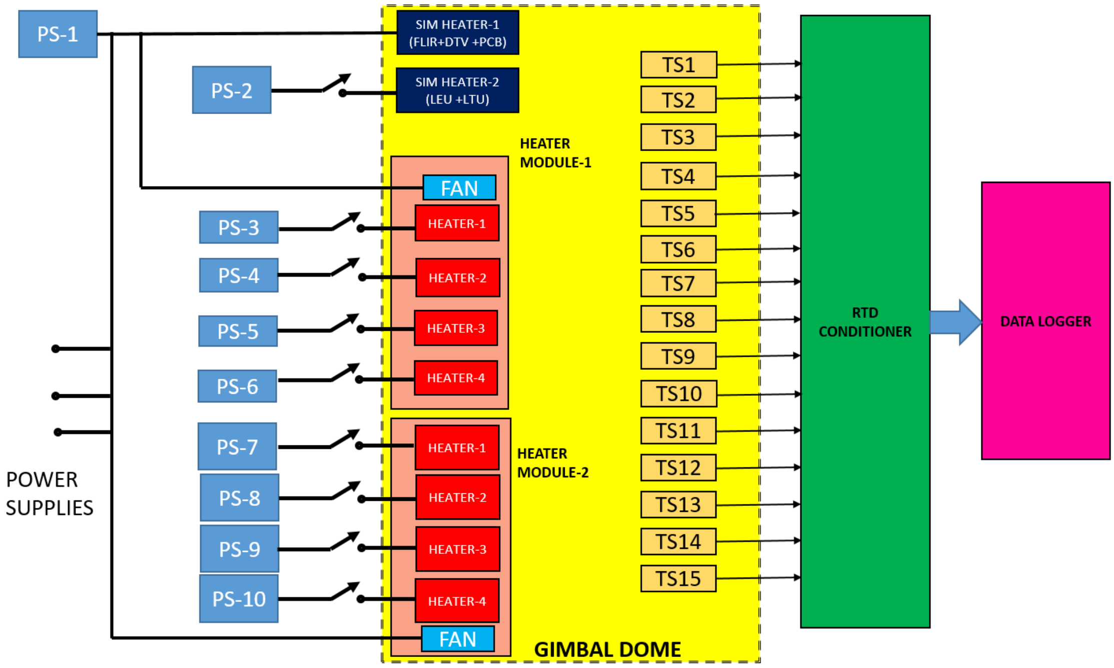

Figure 5: Schematics of power supply &sensors for test set-up

4. Analysis of Data From the Test

The test setup is placed inside the altitude chamber(refer Figure 6) and the following tests are conducted:

1. Fan & heater module-front is functional
2. Fan & heater module-rear is functional
3. Both rear and front modules are functional

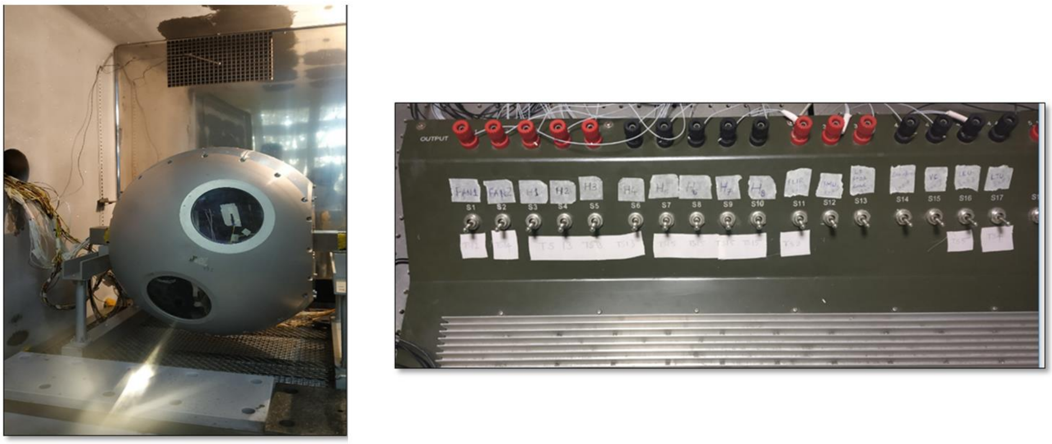

Figure 6: Test-set-up in altitude chamber and the switching unit

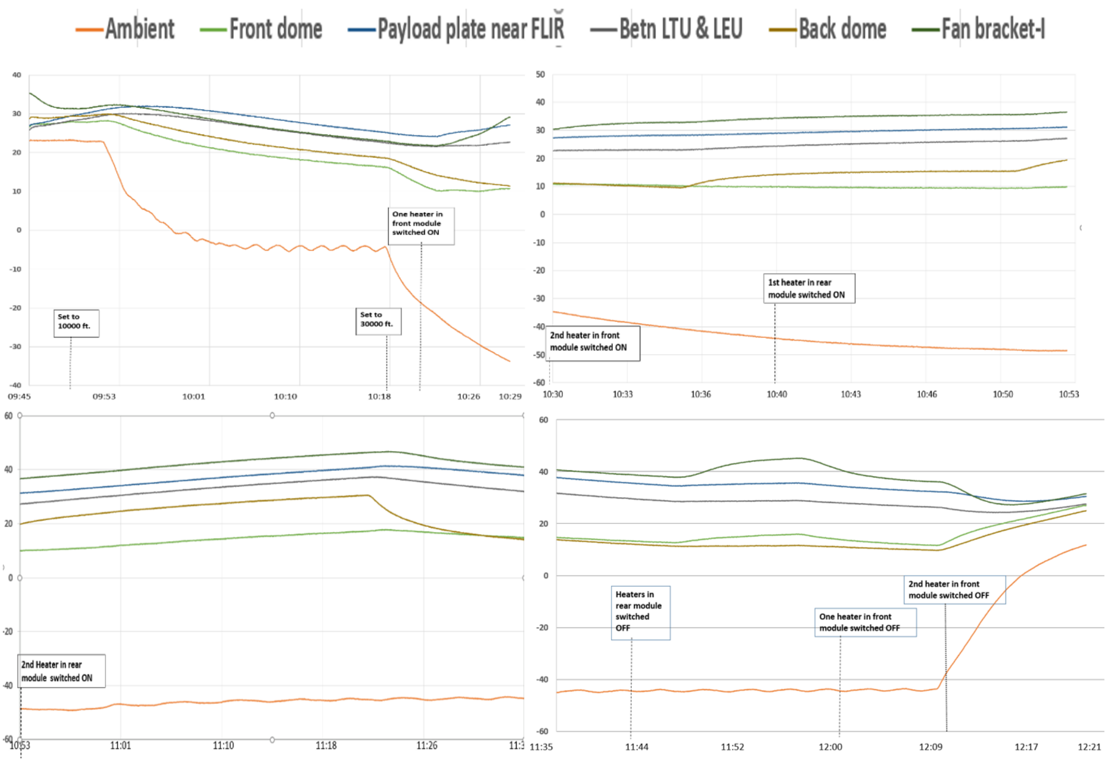

Figure 7: Time V/s Temperature plot measured during one of the experiment when both modules were operated

Figure 7 shows the plot of temperature during one of the experiment conducted when both the modules were operated. The data is logged in data logger and downloaded as excel file. The plots are generated directly from the excel files. As the data logged in each file is limited, the plot is broken in to four graphs. In this particular experiment, 2 heaters of the front module are switched ON and then followed by 2 heaters in the rear module. The heaters are switched ON when the front dome temperature is close to 10^{o}C. They are switched OFF when the temperature monitored on the fan bracket is close to 45^{o}C. The main performance indicators are the temperature monitors namely payload plate near FLIR(TS 7) & Between LTU &LEU(TS 9). Following observations made during experiments helped in evolving the logic for switching ON&OFF of fan & heater in the TMS:

1. The front fan-heater module is more effective in heating the volume as its affect on temperature monitors namely payload plate near FLIR(TS 7) & Between LASER units(TS9) is better.
2. It is very critical to monitor the temperature on the fan bracket.
3. 2 to 3 heaters are sufficient to maintain the temperature at sub-zero conditions when the experiment is conducted in altitude chamber.
4. Inner surface of dome is ideal for placement of thermostats for initiating the operation of heaters.

5. FAN-HEATER LOGIC

The logic for the TMS is derived based on the data collected during the experiments with the TMS test-set-up in the altitude chamber. The logic is as shown in
Figure *8*. TH1 to TH8 are thermostats placed in the chamber and H1 to H4 are the four heaters in the front module. Thermostats used are single pole, single throw surface mounted thermostats. The specifications of thermostats are as in Table 5.

Table 5 RTD sensor distribution in TMS test set-up

Nomenclature	TH1	TH2	TH3	TH4	TH5	TH6	TH7	TH8
Type	Open on rise	Open on rise	Open on rise	Open on rise	Open on rise	Close on rise	Open on rise	Close on rise
Temperature for close	0ºC	15ºC	35ºC	35ºC	35ºC	35ºC	35ºC	65ºC
Temperature for open	21ºC	27ºC	45ºC	45ºC	45ºC	23.8ºC	45ºC	75ºC

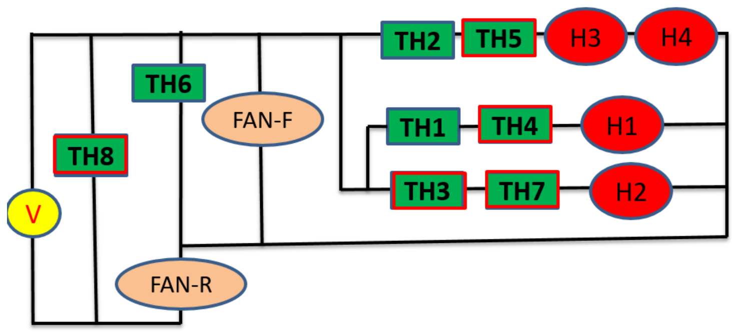

Figure 8: TMS logic

The operation of the logic with thermostats is detailed as follows:

1. Thermostats TH1 and TH2 are placed on the front dome such that they close the circuit to power ON the heaters. When the gimbal is subjected to low ambient temperature, temperature inside the gimbal starts decreasing. When temperature falls to 15°C, TH1 gets closed and heaters H1 & H2 are switched ON. If temperature further drops, TH2 gets closed and heaters H3 & H4 are powered ON. The heat generated by the heaters can be sufficient to prevent the decrease in temperature inside the gimbal. When the temperature rises TH2 and TH1 will open thus switching OFF the power to the heaters.

2. The safety of fan is assured through the temperature safety thermostats TH4, TH5 & TH3 which are provided on fan bracket. These thermostats cut off the power to heaters when the temperature of fan bracket exceeds 45°C, for the safety of the fan. This thermostat will close the circuit only if temperature decreases to temperature that is safe for operation of the fan.
3. Thermostats TH7 is a thermostat placed close of LASER unit. In case the LASER unit is used during operation, the temperature near this point increases beyond 45°C and thus TH7 breaks the circuit to heater H2, thus reducing the power required to be dissipated from TMS.
4. Thermostat TH6 is used to switch between the fans for sharing the duty cycle. Fan-F and Fan-R refers to the fan in the front and rear respectively. It is also ensured that the heaters receive power only when the fan within the module is active. At temperature >35°C thermostat TH6 is at closed condition, and the power is supplied to rear fan. When the temperature reduces to ~24°C, power to front fan is established. Also, the power avaialability to heaters are also established. However, they get powered only when TH1 or TH2 are closed.
5. Thermostat TH8 is for the overall safety of the system. In case due to any malfunctioning, heater bracket temperature reaches 75°C, the power to TMS is cut OFF through TH8.
6. The temperature capacity of thermostats is 7Amps. However, routing the current to heaters through thermostats can result in thermostats carrying currents close to their capacity. Higher current through thermostats can significantly reduce their life. So relays are used in these circuits to ensure that the thermostats are used mostly like switching devices while the power to the heaters are controlled through relay.
7. Two heaters H1 and H2 are in parallel providing power of ~200W while heaters H3 and H4 are connected in series providing power of ~50W.

6. TEST OF FAN-HEATER LOGIC TO MEET FUNCTIONALITY

The fan-heater logic was tested for the Designer specified temperature cycle to prove functionality of TMS with the sensors in the turret switched ON. The details of the test are as in Table6. In this test, temperatures are monitored at points where thermostats are located and around the payload plate. Heater 'ON' & 'OFF' are arrived by analysing the current drawn by the test setup.

Table 6 Details of Designer specified temperature cycle

Altitude (ft)	Temperature (°C)	Pressure (mBar)	Event	Heater Condition as monitored
15000	+0.35	577	A	Heaters 1,2,3 &4 OFF
20000	-9.55	472	B	Heaters 1,2,3 &4 OFF
20000	-9.55	472	C	Heater 1 & 2 ON
20000	-9.55	472	D	Heaters 1,2,3 &4 OFF
25000	-19.35	380	E	Heaters 1,2,3 &4 OFF
25000	-19.35	380	F	Heater 1 & 2 ON
30000	-29.1	300	G	Heater 1 & 2 ON
35000	-40	230	H	Heater 1 & 2 ON
35000	-40	230	I	Heater 1,2,3& 4 ON
SL	+55	1000	J	Heater 1 & 2 ON

SL	+55	1000	K	Heaters 1,2,3 &4 OFF

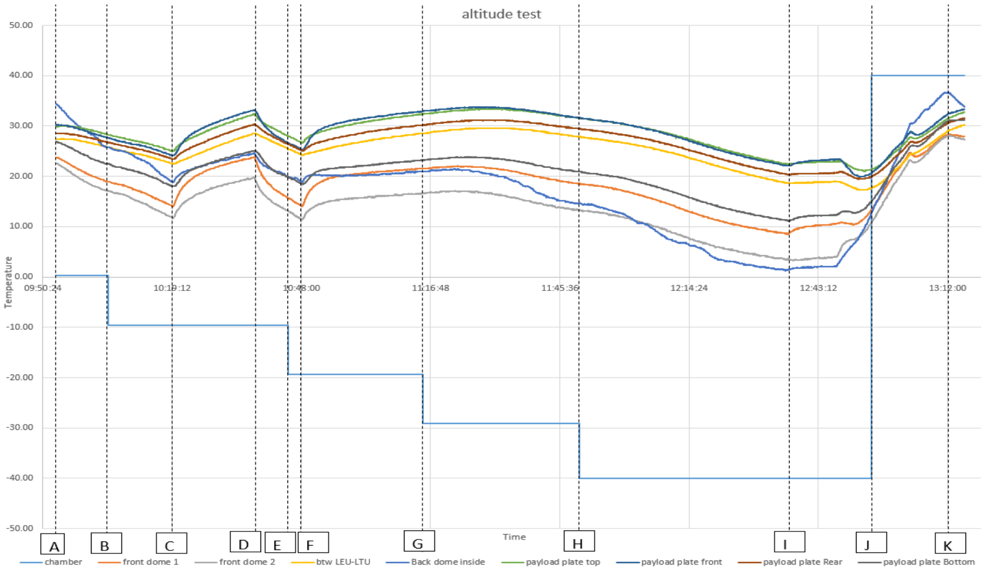

Figure 9: Time V/s Temperature for the Designer specified temperature cycle

The plots during the test is as shown in Figure9. The observations during the experiment are as follows:

1. During event ‘C’ when front dome temperature reaches 15°C. Thermostat TH1 closes and heaters H1 & H2 are switched ON. Temperature inside system starts increasing and reaches 27°C, thermostat TH1 opens and heaters H1 & H2 closes. Temperature again starts decreasing.
2. During event ‘F’ when front dome temperature again reaches 15°C. Thermostat TH1 closes and heaters H1 & H2 are switched ON. Temperature inside system starts increasing and reaches 27°C, thermostat TH1 opens and heaters H1 & H2 closes. Temperature again starts decreasing. The heat is able to sustain the temperature inside the chamber.
3. During event ‘I’, when the temperature of front dome reaches 10°C. Thermostat TH2 closes. Heaters H3 & H4 switches ON. Temperature inside system starts increasing. front dome temperature reaches 21°C. Thermostat TH2 opens. Heaters H3 & H4 switches OFF. Altitude is set at sea level and 55°C. Temperature inside system increases.
4. During event ‘J’ front dome temperature reaches 21°C. Thermostat TH2 opens. Heaters H3 & H4 switches OFF.
5. During event ‘J’, front dome temperature reaches 26°C, thermostat TH1 opens and heaters H1 & H2 switches OFF.
6. The temperatures as monitored payload plate top, payload plate front, payload plate rear and payload plate bottom remained above 10°C. The logic of the TMS as wired could meet the objective to keep the temperature in the optical module above 10°C.

7. Conclusion

Thermal management system for MREO turret is realised and successfully tested for the temperature cycles in the altitude temperature. Also, the tests are repeated for different qualification tests as manadated by aerospace requirements. TMS could meet the objectives for ensuring that the temperature is above 10°C in the optical module during operation at sub-zero temperatures when the turret is ON. It was also observed that the windows didn't have any moisture condensed on them during the tests. TMS so realized through this journey has completed all the required tests with the MREO turret on the ground. The system is successfully integrated with turret to complete the qualification tests of the MREO.

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