Programmable Thermostat Module Upgrade for the Multi-Purpose Logistics Module

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Abstract

The STS-121/ULF1.1 mission was the maiden flight of the Programmable Thermostat Module (PTM) system used to control the 28 V shell heaters on the Multi-Purpose Logistics Module (MPLM). These PTMs, in conjunction with a Data Recorder Module (DRM), provide continuous closed loop temperature control and data recording of MPLM on-orbit heater operations. This paper will discuss the hardware design, development, test and verification (DDT&V) activities performed at the Marshall Space Flight Center (MSFC) as well as the operational implementation and mission performance.

Figure 1: Illustration of MPLM Stowed in Space Shuttle Payload Bay

1.0 Background

The Multi-Purpose Logistics Module (MPLM) is a pressurized module used for transporting International Standard Payload Racks (ISPR), consumable supplies, and various other logistical items to and from the International Space Station (ISS) (Fig.1). The 21 foot long by 15 foot diameter aluminum canister can transport up to 20,000 pounds of payload in a pressure and temperature controlled environment. The environment inside the MPLM is maintained by pressure relief valves (both positive and negative), external multi-layer insulation (MLI) blankets, and a shell heater system located on the structural skin. The internal temperature and pressure of the module are controlled via the heaters to insure the following: (1) to prevent condensation inside the MPLM (60°F max dewpoint) (2) to prevent actuation of either the Positive Pressure Relief Assembly (PPRA) or the Negative Pressure Relief Valve (NPRV) (3) to maintain MPLM internal cabin air temperature between 50-113°F and (4) to maintain MPLM cabin air pressure in the range of 13.9-15.2 psia.

From an operational perspective, an MPLM mission has three distinct phases. Phase 1 occurs from launch thru hatch opening on the ISS. Phase 2 occurs while the hatch is open to the ISS, and phase 3 is the time period between hatch closure on ISS thru landing. Phase 3 is typically the only period when the 28V heaters are operated. During this portion of the mission the MPLM cabin air environment must be maintained between the positive and negative pressure relief valve actuation pressures (PPRA and NPRVs) and above the local dewpoint temperature.

The initial MPLM shell heater system design utilized 3200 Series Elmwood Thermostats to provide temperature control. Unfortunately, the thermostat setpoints were so high (81 to 95 °F setpoint range) that the MPLM PPRAs would actuate during a nominal mission timeline. The risk of actuating PPRAs during on-orbit operations could jeopardize MPLM mission objectives if a valve failure were to occur. This scenario would result in the loss of valuable make-up consumables from either the ISS or Space Shuttle. Furthermore, the higher setpoints required additional Shuttle cryogenic resources to operate the fuel cell power supply used to drive the MPLM shell heaters.

To compensate for the high setpoints the MPLM shell heaters were operated manually. Heater switches, located in the Shuttle's aft flight deck, were cycled on/off by the flight crew. Preflight thermal analyses were used to define approximate heater duty cycles, while real-time telemetry was used to "fine-tune" the heater on/off times to meet mission objectives. This effort required real-time Mission Operations Directorate (MOD) support to coordinate crew activities in order to perform these tasks. Another drawback of manual heater operations lies in the fact that the MPLM shell heaters could only be operated while the crew was awake. Extended heater cycles during crew sleep periods could raise the internal MPLM air pressures above the PPRV pressure limits. These constraints proved to be both cumbersome and inefficient for real time flight operations.

In October 2000 the MPLM project office presented a proposal to the ISS Program Office for developing a solid-state programmable thermostat which would replace the bi-metallic disk-style devices.

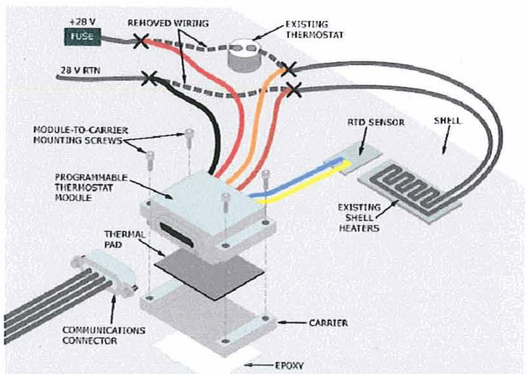
These solid-state thermostats offered several advantages including tighter temperature control, selectable setpoints, and closed-loop feedback control capability. These features, in turn, would result in greater operational flexibility during future ISS missions.

This paper discusses the PTM project development cycle and first time use of these state–of-the-art thermostats.

2.0 MPLM Programmable Thermostat System

The MPLM has two sets of heaters and thermostats, one operating on 28V power and one operating on 120V power. The 28V string is powered from the Space Shuttle's fuel cell power supply and is used while the MPLM is in the Shuttle's Payload Bay. The 120V string is powered by the ISS and is used when the MPLM is attached to the ISS. The 28V heater system consists of 22 thermostatically-controlled heater circuits and 66 individual Kapton resistive element heater pads. Only the 28V thermostats were replaced with the new PTMs.

Figure 2 is an illustration depicting the new PTM and its coupled sensor, an external Resistive Temperature Device (RTD). The PTM module design consists of a secured printed wiring board assembly mounted in an aluminum housing. The aluminum housing is affixed to a mounting bracket with 4 set screws. The carrier bracket, in turn, is secured to the MPLM pressure shell with a high strength epoxy adhesive. This installation design allows for easy replacement of failed units. Real-time temperature monitoring is accomplished with the RTDs.



MPLM PROGRAMMABLE THERMOSTAT HARDWARE

Figure 2: Programmable Thermostat Hardware

In the upgraded 28V heater network, 20 PTM/RTD assemblies and a data recorder module (DRM) replaced the bi-metallic disk-type thermostats. The DRM records various PTM flight parameters (temperature, on/off status, and other associated health monitoring parameters).
Two circuits were left unchanged in the new configuration as a result of design constraints.

Each PTM/DRM module contains two interfaces. One is an electrical interface, while the other is the communications link for command and data handling (C&DH). The electrical interfaces consist of the 28V power supply/return and RTD wiring, while the C&DH interface is achieved thru a RS-485 communications cable and 21 pin micro "D" metal shell connectors. The DRM interfaces are identical to the PTMs with the exception of the RTD pigtail leads.

The PTM electrical installation was accomplished by clipping the leads at the bi-metallic terminal interfaces and splicing into the main 28V harness power supply/return lines. The RTDs were mounted no more than 36 inches (and no closer than 6 inches) from the PTMs near the existing bi-metallic thermostats. Mounting distances were optimized thru thermal analysis utilizing Systems Improved Numerical Differencing Analyzer (SINDA). The maximum distance is driven by the controllability of the heater zones while the minimum distance is chosen to avoid thermal contamination of the sensor by the controller.

Key design features of the PTM system include:

- Size: 2.25" x 1.75" x 0.5"
- Weight: < 75 gm (w/o carrier); < 100 gm (w/carrier)
- C&DH: RS-485 serial communication protocol
- Software: Graphical Users Interface (GUI) developed for programming and monitoring
- Input Power: +9 to +28 VDC.
- External RTD temperature sensor
- External Heater : Up to 5A at +28VDC
- Programmable temperature set points and span. Setpoint/ span resolution: 0.1 °C
- Data Recorder Module (DRM) available in the same housing for recording status and temperature data for up to 32 PTM units connected on a single RS-485 bus.

Figure 3 is the electrical block diagram of the new MPLM 28V PTM heater network. The RS-485 communication cable provides the C&DH link for the 20 PTMs and DRM. A Ground Support Equipment (GSE) computer is used to upload PTM control parameters (setpoints, error span, and data acquisition rates) during pre-mission ground processing operations at KSC. Post-mission data retrieval is also performed with the GSE computer. No C&DH capability is available during real-time mission operations.

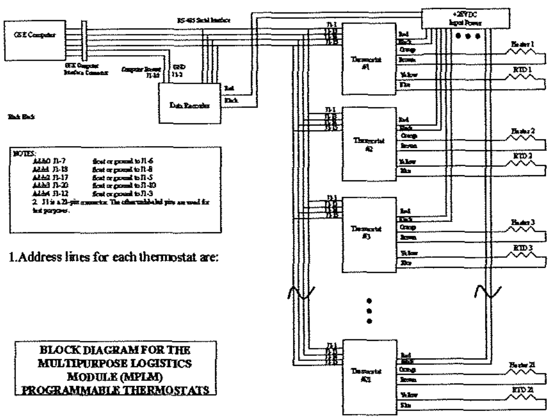


Figure 3: MPLM PTM Electrical Block Diagram

3.0 Hardware Development

The MPLM project office at NASA's Marshall Space Flight Center (MSFC) was responsible for managing all of the Design, Development, Testing, and Verification (DDT&V) activities of the PTM project. DDT&V activities, including Environmental Flight Qualification and Acceptance testing, were performed using the available infrastructure and engineering support personnel at MSFC. The PTM circuit boards were outsourced to a local electronics vendor for manufacturing. However, the final electronics box-level assembly operations, including potting and wire staking, were completed at MSFC.

The Boeing/Huntsville division was responsible for providing the RS-485 communication cable design drawings, while the Boeing/KSC division completed the manufacture, test certification, and installation of the flight cable. MSFC relied upon ALTEC (Italian Space Agency MPLM sustaining engineering partner) to provide detailed installation drawings of the PTM mounting design and RS485 cable routing layout to KSC.

3.1 Radiation Susceptibility Tests

A key decision made early in the project design phase involved using Industrial grade EEE parts in the circuit board design in lieu of more expensive radiation hardened parts. The technical risk was judged to be acceptable, as the on-orbit thermal environment is consistent with industrial grade parts qualifications. Furthermore, the PTMs are located in a benign radiation environment underneath external MLI blankets and micrometeoroid shielding.

To demonstrate the functional capability of these parts in a space environment, a series of radiation tests were performed on prototype units. Two thermostats and a data recorder were subjected to "Proton" or "Heavy Ion" testing at the Indiana University Cyclotron Facility for Single Event Effects (SEE). These units were subjected to an equivalent amount of radiation that would be expected in ten years of continuous operation on the ISS.

The test results demonstrated that the data recorder and thermostat units exceeded the on-orbit Mean Time Between Failure (MTBF) design requirement of 365 days (equivalent MPLM 25 mission life design requirement) without error or incident. The MTBF design limit for these components was determined to be 447.5 days. This was for the DRM. The PTMs exhibited no effects from the radiation testing. The DRM MTBF limit was due to data memory effects. However, the DRM design contains redundant memory banks to compensate for this.

A design waiver was approved by the ISS EEE Parts Board upon successful completion of these radiation tests.

3.2 Bond Strength Tests

Two bonding tests were performed to assess the bonding material and installation procedure of the PTM/DRM carrier brackets to the MPLM pressure shell. The installation procedure was based on a Micro-Tau strain gage bonding process developed at KSC. RTV-566 epoxy adhesive is the bonding agent used for the PTM carrier bracket mounting design.

A single PTM was mounted on a Space Shuttle Solid Rocket Booster (SRB) test fixture to perform vibration development testing of the PTM carrier bracket mounting concept. The SRB test fixture was chosen for the development testing as its radius of curvature is approximately equal to that of the MPLM structural shell.

Prior to performing the bond/vibration tests, a static load test was performed (in shear plane) on the bonded PTM. The PTM remained affixed to the SRB test fixture and successfully met the 70 lbf. strength requirement called out in the Micro-Tau procedure.

A second bond test was performed to determine the ultimate tensile strength of the RTV-566 adhesive bond. The "pull to failure" ultimate strength of the RTV-566 adhesive was measured to be 1116 lbf. in the shear plane.

The results obtained from these development tests validated the PTM RTV-566 mounting installation concept.

4.0 Hardware Qualification & Acceptance

All PTM qualification and acceptance testing was performed at MSFC's environmental test facilities. This included electrical emissions induced/conductance (EMI/EMC), random vibration/ structural, and thermal cycle flight testing.

Figure 4 is the test fixture developed for the PTM flight qualification/ acceptance testing.

Figure 4: MPLM PTM Environmental Test Fixture

Flight certification testing utilized a lot qualification/ acceptance test approach. A special test fixture was designed to accommodate 25 PTM/DRM units during a single test flow sequence.

All testing was performed in accordance with the standards and guidelines established by the ISS program in SSP41172, "Qualification and Acceptance Environmental Test Requirements". EMI/EMC test standards are defined in NSTS-21000-IDD-ISS, "International Space Station Interface Definition Design Documents".

Each PTM and DRM was acceptance-tested to ensure workmanship only at the electronic box assembly level; no component testing was performed at the circuit board assembly level. Instead, quality surveillance was maintained at the vendor's facility through visual workmanship and inspection audits at all levels during the printed circuit board manufacturing process. These audits were performed prior to component testing of the potted electronic module assemblies. A total of 100 PTM assemblies and 6 DRM units were manufactured in this development effort.

Figures 5 and 6 are flowcharts representing the environmental test flow paths performed during this hardware development campaign. Ten PTMs and a single DRM were tested during the flight qualification phase, while four separate hardware acceptance test flows were completed on the remaining PTM/DRM units. The first 3 acceptance test lots consisted of 23 PTMs and 1 DRM, while the final acceptance flow consisted of 24 PTM and 2 DRMs.

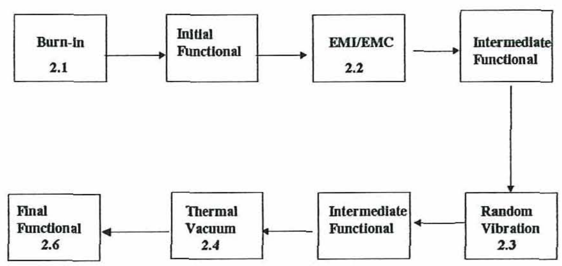


Figure 5: PTM Flight Qualification Test Flowchart

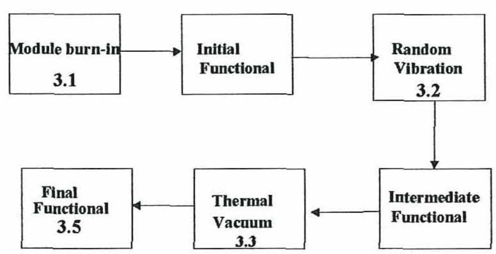


Figure 6: PTM Flight Acceptance Test Flowchart

Table 1 lists the component test matrix for all of the PTM/DRM hardware tested. This matrix cross-references which qualification or acceptance tests each PTM or DRM unit was subjected to. Module-level electronic burn-in tests were performed on all of the PTM/DRM units prior to the environmental testing. For the EMI/EMC qual tests, only the 1st manufactured PTM and DRM units were subjected to EMI/EMC tests prior to start of the flight qualification testing.

Component	Burn-In	Qualification			Acceptance	
		EMI/EMC	Vibration	Thermal	Vibration	Thermal
Thermostat						
1	x	x	x	x		
2 thru 10	x		x	x		
11 thru 100	x				x	x
Data Recorder						
1	x	x	x	x		
2 thru 6	x				x	x

Table 1: MPLM Programmable Thermostat Component Test Matrix

The vibration levels and thermal cycles for the qualification tests were set such that the hardware is qualified for 25 flights – the design mission life of each MPLM. Figure 7 lists the qualification and acceptance vibration levels, while Figure 8 lists the qualification and acceptance thermal cycling temperature ranges. These levels are defined in the PTM and DRM End Item Specification documents.

It should be noted that all testing performed during flight qualification and acceptance was successful with no hardware failures noted.

Frequency (Hz)	Qualification Level	Acceptance Level
20	0.04 g^2/Hz	0.01g^2/Hz
20 to 65	+7.6 dB/Octave	+7.6 dB/Octave
65 to 180	0.8 g^2/Hz	0.2g^2/Hz
180 to 360	-7.0 dB/Octave	-7.0 dB/Octave
360	0.16 g^2/Hz	0.04 g^2/Hz
360 to 1400	-2.6 dB/Octave	-2.6 dB/Octave
1400	0.05 g^2/Hz	0.0125 g^2/Hz
1400 to 2000	-4.9 dB/Octave	-4.9 dB/Octave
2000	0.028 g^2/Hz	0.007 g^2/Hz
Composite	16.8 g_{rms}	8.4 g_{rms}

Qualification Duration = 810s in each of 3 mutually perpendicular axes.
Acceptance Duration = 60s in each of 3 mutually perpendicular axes.

Figure 7. Qualification and Acceptance Vibration Levels.

	Low Temperature	High Temperature	# of Cycles
Qualification	-24°F	+156°F	24
Acceptance	-4°F	+136°F	8

Figure 8. Thermal Cycle Ranges.

5.0 STS-121 MPLM Shell Heater Operations

The STS-121/ ULF1.1 ISS mission was launched on July 4, 2006. This was the first flight of the fully automated MPLM 28V shell heater system. During the six previous MPLM missions the shell heaters were manually cycled to maintain temperature/ pressure control within power requirements defined in the ISS Mission Integration Plan (MIP). Beginning with this mission, however, the automated PTM system posed new challenges for conducting the MPLM heater operations. This lies in the fact that the PTMs cannot be re-programmed from the ground during flight operations.

In order to meet operational requirements with the PTM heater system a new flight rule had to be developed for the STS-121 mission. This rule defined the range of acceptable cabin air temperature/ pressure (T/P) conditions prior to MPLM hatch closure. The desired ISS cabin air properties are functions of the final MPLM cabin air temperature and the NPRV/ PPRA crack pressures.

The ISS closeout conditions were derived in the following manner:

$$T_1 = P_1\left(\frac{T_2}{P_2}\right)$$

where:

T_1 = ISS closeout air temp
T_2 = MPLM final air temp
P_1 = ISS closeout air pressure
P_2 = NPRV/ PPRV minimum crack pressure

T_1 values represent ISS closeout air temperatures. These temperatures are calculated over a range of P_1 closeout pressure conditions. T_2 is the MPLM cabin air temperature at deorbit. This is represented by the steady-state MPLM shell temperature (PTM heater setpoint). P_2 pressures are the minimum as-tested crack pressures of the NPRV and PPRA valves flown during this mission.

PTM temperature control errors were simulated by adjusting T_2 values upward or downward by the temperature control span. A temperature control span of 0.4 °F was selected for this mission. This ensured that a tight control range about the desired setpoint would be maintained at all times. For the NPRV limit line calculations, T_2 values were adjusted downward. For the PPRA limits, these values were adjusted upward.

T_1 temperatures were plotted against P_1 closeout pressures. The resultant T/P curves define the NPRV and PPRA crack pressure limits at MPLM hatch closure. Any ISS cabin air T/P combination that lies between these limit lines and above the ISS local dew point will satisfy pressure and condensation requirements for the MPLM hardware.

ISS closeout conditions for 6 discreet PTM setpoint cases were analyzed for this mission. The optimum mission setpoint was selected from the corresponding closeout chart which completely bounded ISS cabin air T/P conditions between the NPRV/ PPRA crack pressure envelope.

Figure 9 is the MPLM/ ISS Closeout Flight Rule that was developed for the STS-121 mission. This flight rule is based on a 78 °F PTM heater setpoint. The corresponding heater control range is 77.6 – 78.4 °F (25.2 - 25.6 °C).

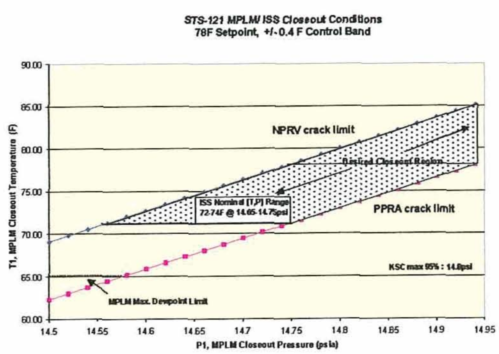


Figure 9: STS-121 MPLM/ ISS Closeout Conditions

Finally, a thermal analysis was performed to determine whether the PTM mission setpoint would meet the STS-121 MIP power budget requirements. The MPLM heater power assessment was completed by ALTEC using the SINDA thermal analysis software program. The SINDA model assumed nominal Shuttle Bay-to-Earth orbital heating rates and an ISS closeout air temperature of 72 °F for the initial conditions in the analysis.
The ALTEC analysis predicted 28kWh of heater power used during nominal timelined heater operations with an additional 8kWh used during mission extension days. The STS-121 MIP allocated 30.5 kWh of heater power for nominal operations (at 278h MET) and 16kWh power for the additional contingency orbit days. The ALTEC model results met the STS-121 MIP requirements and were presented to JSC's STS-121 Joint Operations Panel for formal flight approval.

Figures 10 and 11 are the predicted heater power levels predicted by the ALTEC SINDA model.

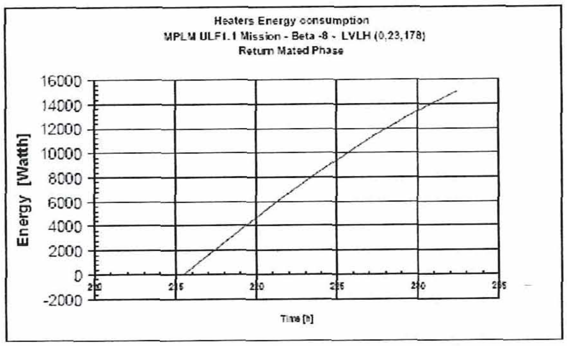


Figure 10: Predicted MPLM 28V Shell Heater Power (217h-230h MET)

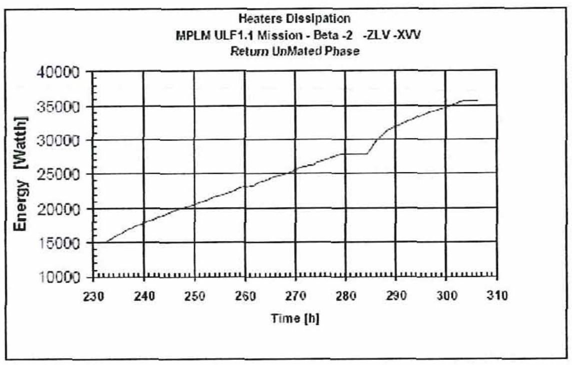


Figure 11: Predicted MPLM 28V Shell Heater Power (230h MET-EOM)

6.0 STS-121 PTM Data Analysis

The STS-121 flight was the first time in which MPLM shell temperatures were recorded during ISS flight operations. The data obtained from the DRM indicated that the PTM system performed exceptionally well. The MPLM shell heaters operated 61 hours, beginning shortly after the MPLM was returned to the Shuttle payload bay and ending approximately 1 hour prior to de-orbit operations.

Post-mission data analysis indicated that all 20 PTMs functioned as designed and maintained the MPLM shell temperatures within the expected temperature control band. The Flight Day 12 (FD12) telemetry data obtained during the MPLM environment check indicated that some of the individual heater circuits had begun cycling off. This was verified by current readings recorded on the heater circuit screen displays.

Figures 14 and 15 are plots of the shell heater energy and power profiles, respectively. Figure 14 shows the total heater energy calculated from the recorded heater on/off duty cycles. A total of 23 kWh of energy was used during the STS-121 mission, slightly less than ALTEC's predicted model value.

Figure 15 shows the heater power profile. The shell heaters were running at 100% duty cycle during the first 6 hours of heater operations.

The lower than expected energy usage is attributed to off-nominal flight attitudes flown during the last two mission days, as the Shuttle was oriented in port-side, sun-facing trajectory (-Y direction) during portions of FDs 12 and 13. These unplanned flight trajectories were driven by problems associated with the Shuttle's APU fuel system. Figure 12 is an isometric view of the MPLM External Configuration, while Figure 13 references the coordinate system of the MPLM in the Shuttle's payload bay. The Shuttle's –Y axis points to the port side of the MPLM. This direction points outward from the FRGF located below the support bracket for the Fluid PDA assembly shown in Figure 12. The Shuttle -X axis points outward from the Forward Endcone.

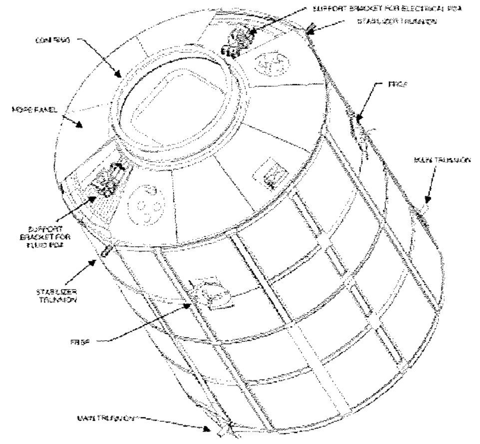


Figure 3.1-1. MPLM External Configuration

Figure 12: MPLM External Configuration

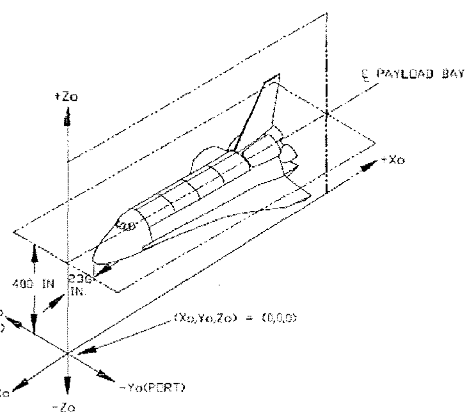


Figure 13: Shuttle Orbiter Coordinate System

The thermal effects arising from the Shuttle -Y port attitudes are illustrated in some of the individual PTM temperature profile plots below. These influences are especially dramatic in Figures 17 and 18. Figure 17 is the MPLM Grapple Fixture temperatures (FRGFs in Fig.12). These fixtures are almost 180 ° apart, with the GRAP –Y PTM facing the sun. This PTM circuit remains off during the port maneuvers, while the GRAP +Y PTM cycles continuously, as this location is shaded. These effects are also illustrated in the Aft Cylinder and CBM temperatures profiles as well (Figs 16 and 18).

Finally, Figure 17 illustrates the tight control response of the PTM system. The grapple fixture on/off status is overlaid with the temperature data. These PTMs cycle within the desired temperature control range of 25.2 - 25.6 °C.

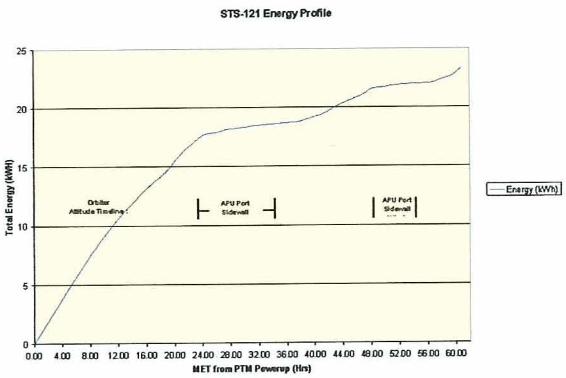


Figure 14: MPLM Heater Energy Profile

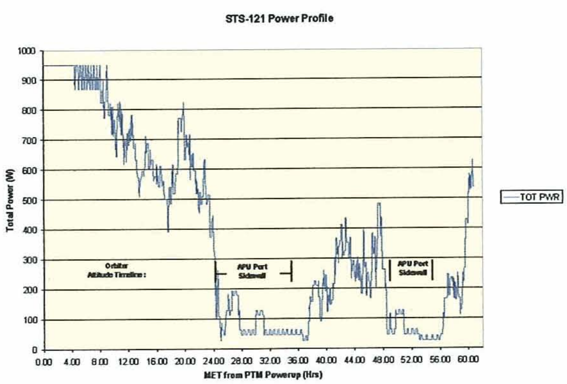


Figure 15: MPLM Heater Power Profile

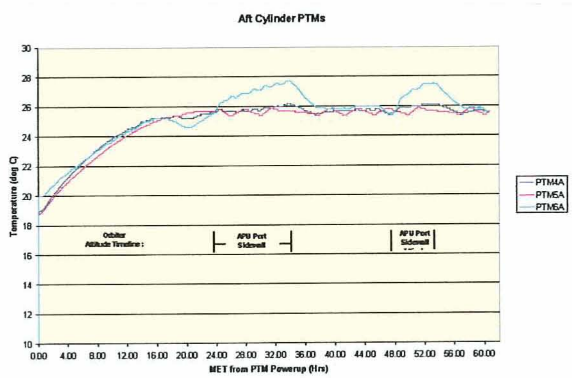


Figure 16: MPLM Aft Cylinder PTM Temperatures

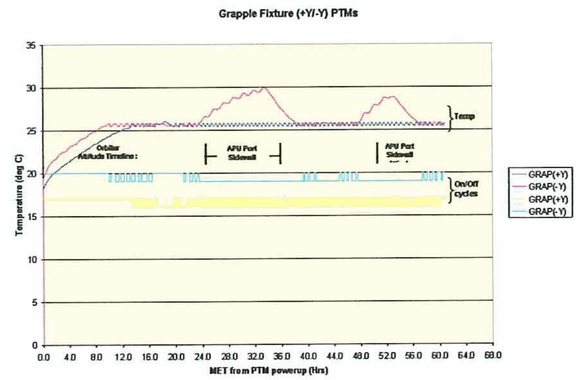


Figure 17: MPLM Grapple Fixture PTM Temperatures

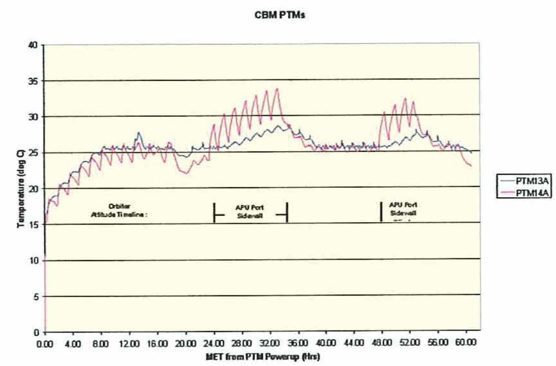


Figure 18: MPLM CBM PTM Temperatures

7.0 Future Applications

The results obtained from the first flight of the PTM shell heater system are very encouraging. Although the PTMs were developed specifically for the MPLM 28V shell heater control system, its design is flexible and can be tailored to meet future customer needs. Below are just some of the customer defined parameters that these designs can accommodate:

- Mounting configurations
- External temperature sensor RTD, thermal couple, thermistor, other temperature sensing devices
- Heater Current
- Supply Voltage
- Range of temperature measurement and control.

Three disclosures of inventions (patents) have been filed for these technologies. They are as follows:

MFS-32000-1 "Miniature Housing with Standard Addressable Interface for Smart Sensors and Drive Electronics"
MFS-32209-1 "Programmable Data Logger/Master Controller with Multiple Sensor/Device Interface"
MFS-31815 "Distributed Solid State Programmable Thermostat/Power Controller"

8.0 References

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12. ALTEC Report AL-TN-ALTEC-0016 Issue 2, "MPLM Thermal Analysis for STS-121 Mission", 06/20/2006

9.0 Acronyms

ALTEC	Advanced Logistics Technology Engineering Center
APU	Auxiliary Power Unit
CBM	Common Berthing Mechanism
C&DH	Command and Data Handling
DDT&V	Design, Development, Test & Verification
DRM	Data Recorder Module
EOM	End of Mission
EMI/EMC	Emissions Induced/ Compatibility
FD	Flight Day
FRGF	Flexible Releasable Grapple Fixture
GMT	Greenwich Mean Time
GSE	Ground Support Equipment
ISPR	International Standard Payload Rack
ISS	International Space Station
JSC	Johnson Space Flight Center
MET	Mission Elapsed Time
MIP	Mission Integration Plan
MLI	Multi-Layer Insulation
MOD	Mission Operations Directorate
MPLM	Multi- Purpose Logistics Module
MSFC	Marshall Space Flight Center
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NPRV	Negative Pressure Relief Valve
PPRA	Positive Pressure Relief Assembly
PTM	Programmable Thermostat Module
RTD	Resistive Temperature Device
SEE	Single Event Effects
SINDA	Systems Improved Numerical Differencing Analyzer
SRB	Solid Rocket Booster
STS	Space Transportation System
T/P	Temperature/Pressure