SPACE SCIENCE PAYLOADS
OPTICAL PROPERTIES MONITOR (OPM)
MISSION FLIGHT ANOMALIES THERMAL ANALYSES

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ABSTRACT

The OPM was the first space payload that measured in-situ the optical properties of materials and had data telemetered to ground. The OPM was EVA mounted to the Mir Docking Module for an eight-month stay where flight samples were exposed to the Mir induced and natural environments. The OPM was comprised of three optical instruments; a total hemispherical spectral reflectometer, a vacuum ultraviolet spectrometer, and a total integrated scatterometer. There were also three environmental monitors; an atomic oxygen monitor, solar and infrared radiometers, and two temperature-controlled quartz crystal microbalances (to monitor contamination). Measurements were performed weekly and data telemetered to ground through the Mir data system. This paper will describe the OPM thermal control design and how the thermal math models were used to analyze anomalies which occurred during the space flight mission.

BACKGROUND

In 1986, the National Aeronautics and Space Administration (NASA) Office of Aeronautics and Space Technology (OAST) released an Announcement of Opportunity (AO) under the In-Space Technologies Experiment Program (IN-STEP). This AO was issued to seek new experiments for space flight that were under development by contractors or new experiments that were unable to be developed because of cost constraints. In response to this AO, the OPM experiment was proposed as an in-space materials laboratory to measure in-situ the effects of the space environment on thermal control materials, optical materials, and other materials of interest to the aerospace community. The OPM was selected and funded.. The Marshall Space Flight Center (MSFC) in Huntsville, Alabama managed the project.

The OPM was launched on STS-81 on January 12, 1997. Mounted in a SpaceHab Double Rack, the OPM was Intravehicular Activity (IVA) transferred into the Mir Space Station on January 16, 1997. It was stowed for two and one-half months before deployment and powered up on the Mir Docking Module by the first joint Russian-American Extravehicular Activity (EVA) on April 29, 1997. On June 25, 1997, the OPM lost power because of the Progress collision into Mir's Spektr module and did not regain operational status until September 12, 1997. The OPM continued operation until January 2, 1998 when the OPM was powered down in preparation of the January 8, 1998 EVA to retrieve the OPM. After a successful Russian EVA retrieval, the OPM was later transferred IVA into the Shuttle (STS-89) and returned to Kennedy Space Center (KSC) on January 31, 1998.

A detailed description of the OPM Experiment including an overview of the system design and mission performance is provided in the “Optical Properties Monitor (OPM) System Report” [1]. Figure 1 is a photograph of the deployed OPM. The OPM is seen near the 2 o’clock position on the Docking Module. Figure 2 illustrates the OPM mounting orientation on the Mir Space Station. The baseline layout of the internal hardware is illustrated in Figure 3. This layout shows the locations of the electronics boxes, experiment subsystems, and sample carousel.

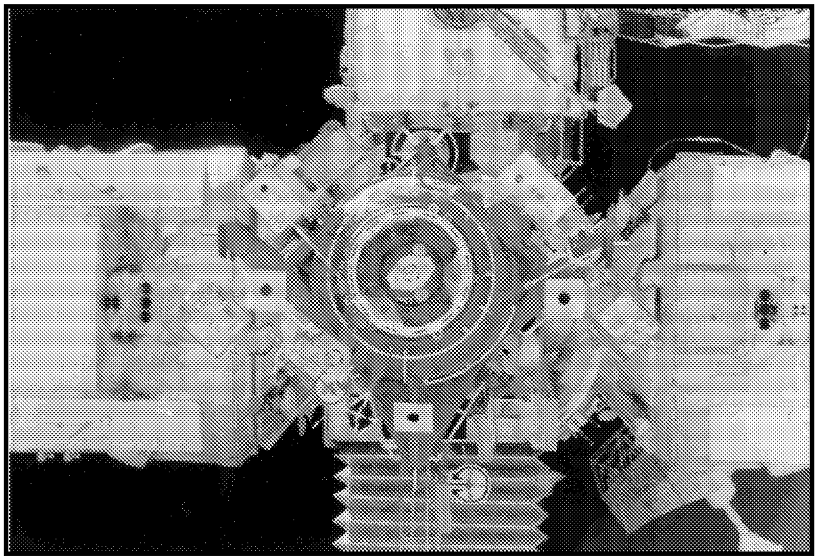

Figure 1: OPM on MIR (Docking Module End View).

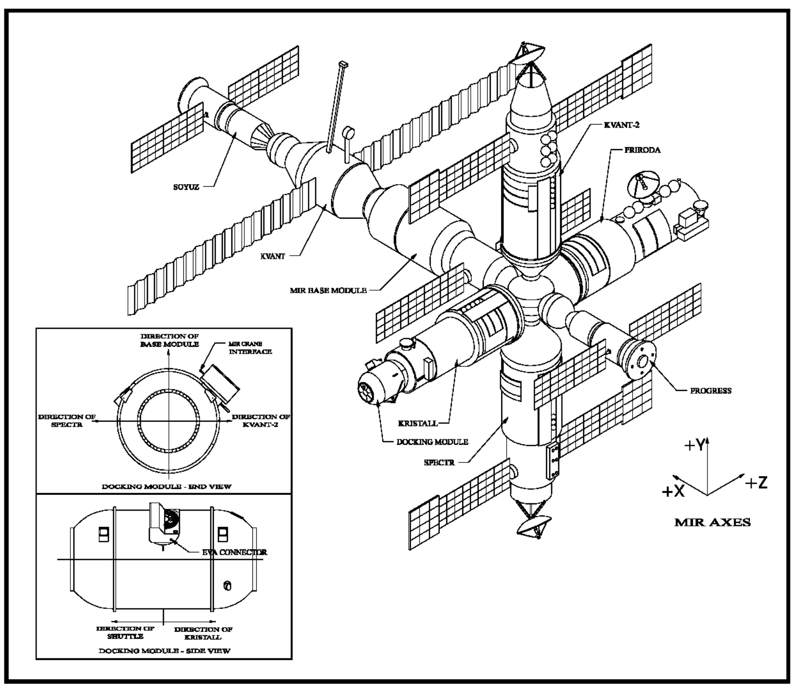

Figure 2: OPM Mounting Orientation on the Mir.

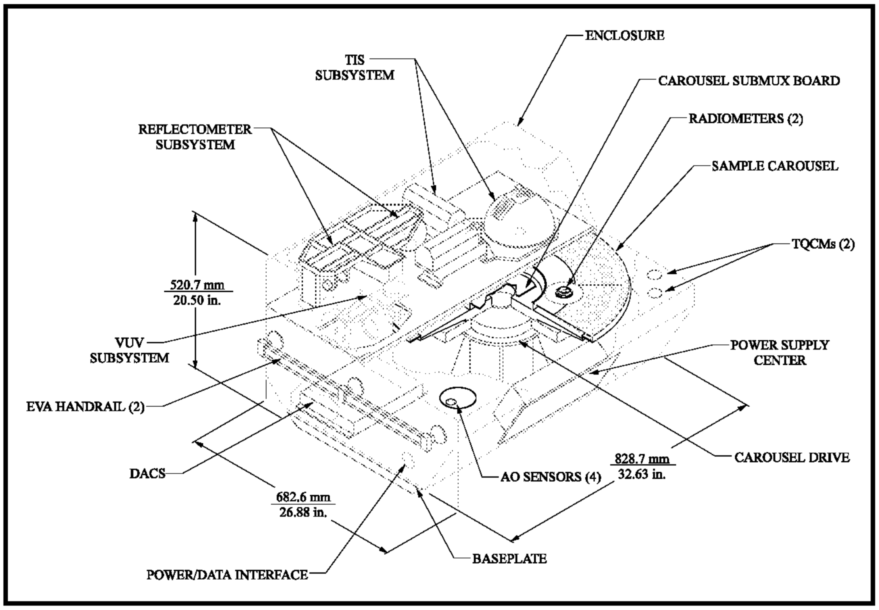

Figure 3: Layout of the Internal Hardware of the OPM.

OPM THERMAL CONTROL

The OPM experiment was modeled using SINDA'85/FLUINT[2] and TRASYS[3] to calculate the conduction and radiation heat transfer between the internal OPM components as well as its external environment. To assist in the accuracy of the model predictions, the OPM was added to the integrated Mir/Docking Module thermal models obtained from NASA/JSC[4,5]. The results of the predicted thermal values dictated how the OPM thermal design was achieved for hot, cold, and nominal operating conditions. Further, the OPM timeline was analyzed to minimize peak input power requirements (kilowatts [kW], not kilowatt-hour [kWh]) and assess the internal temperature fluctuations to the OPM. These predicted thermal extremes were not to exceed the component minimum and maximum operating temperatures. Indeed, the OPM timeline was changed to modify the proposed measurement sequence which decreased the component temperature extremes and peak power (kW). However, the measurements sequence duration increased, increasing the total kWh.

Based on model predictions and the modified weekly timeline, the OPM was designed for passive thermal control with active heaters to maintain a minimum temperature of 0°C. The heaters maintained thermal control during the quiescent periods of operation when the OPM was operating in monitor mode (i.e. not performing measurements). During the measurement sequence, the heaters were switched off and the external thermal control coatings coupled with the thermal capacitance of the OPM provided sufficient thermal control. The OPM heater system design, located on the emissivity plate, consisted of two heater circuits with two 15-watt heater elements mounted in parallel in each circuit. Heater control was effected by using thermistors on this plate to thermostatically control their operation. Heater setpoints were selected approximately at 4°C (on) and 7°C (off). Thermal control was evaluated for materials exposed directly to the space environment as well as those not exposed. For exposed surfaces, the temperature control was achieved by the combination of various types of thermal control coatings, some having low solar absorptance or high solar reflectance coupled with either low thermal emittance (AZT custom coating) or high thermal emittance (white coating) in order to control absorption of direct solar irradiance and reflected solar irradiance from Mir and/or the earth (albedo). Low thermal emittance coatings were used to minimize radiation from selected OPM panels while high thermal emittance coatings were used on other panels to maximize the thermal radiation. The unexposed surfaces were covered with MLI to minimize heat transfer. The combination of materials provided the necessary thermal control to match the measurement sequence and overall timeline with the expected Mir environment.

The “Thermal Data Book for the OPM Experiment” [6] documents the details of the OPM thermal control system design including the TRASYS geometric math models, the SINDA thermal math models, the design analyses, and the thermal vacuum test program which was used to verify the math models. The “Mission Thermal Data Book for the OPM” [7] documents the OPM thermal flight data including the use of the thermal math models to evaluate the flight anomalies. A typical thermal profile, predicted by the models for the measurement sequence and compared to flight data, is shown in Figure 4.

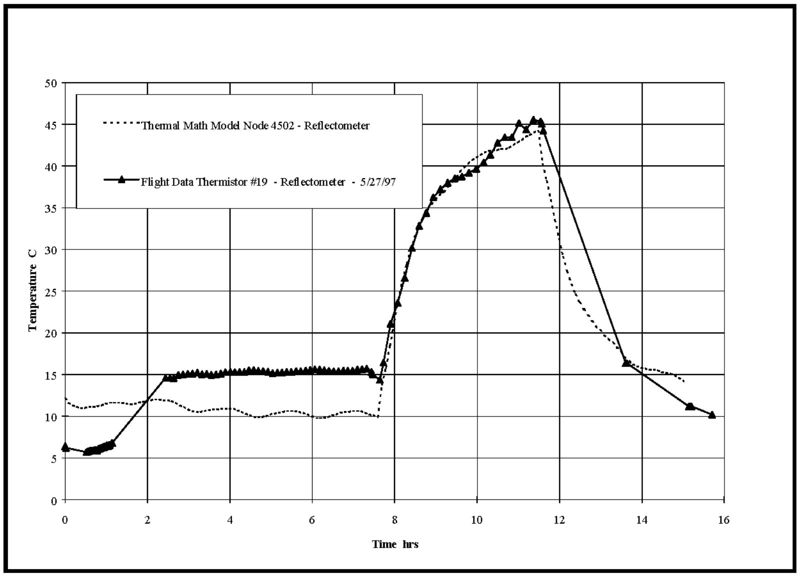

Figure 4: OPM Reflectometer Thermal Profile for the Measurement Sequence

INSTRUMENTATION

The OPM thermal instrumentation consisted of 31 thermistors. Each of the 31 thermistors is either epoxied directly to the OPM structure or epoxied into an aluminum-mounting block mechanically attached to the OPM structure. Table 1 provides a description of the 31-thermistor mounting locations.

Temperature data was recorded for each of the 31 thermistors throughout each of the 27 OPM measurement sequences/timelines. The nominal OPM measurement cycle timeline is shown in Figure 5. Figure 6 shows the combined set of 27 measurement cycle temperature profiles for Thermistor T28 located on the OPM Base Plate.

Temperature data was recorded for each of the 31 Thermistors throughout the mission while in the monitoring mode. Temperature monitor data was recorded using two different time intervals. For one two-hour period each day the monitor data was recorded using two-minute intervals. Figure 7 is an example of the two-minute monitor data for May 6-7 1997. This data provides information on the temperature variations that occur during a single 90-minute orbit. For the remainder of the day the monitor data was recorded using a two-hour time interval. This data provides information on the temperature variations that occur over a twenty-four hour period (sixteen orbits). The two-minute and two-hour monitor data have been combined into a single overall monitor data set.

All of the critical electronic components are mounted on either the Base Plate or the Emissivity Plate. During the monitoring mode (non-measurement cycle) all of the component temperatures are driven by one of these two locations. Figure 8 presents the temperature monitor data for the OPM Base Plate Thermistor (T28) and Emissivity Plate Thermistor (T09) for the month of June 1997.

Table 1: OPM Thermistor Mounting Locations.

Thermistor #	Description	Location	Thermistor #	Description	Location
T00	Thermistor VR1	Carousel Tray 6	T16	Encl. Top Panel #1	Top Panel- TQCM Side
T01	Thermistor VR2	Carousel Wheel 6	T17	Encl. Top Panel #2	Top Panel - AO Side
T02	Thermistor VR3	Carousel Wheel 7	T18	Reflectometer #1	Flex Mirror Mount
T03	Thermistor VR4	Carousel Tray 7	T19	Reflectometer #2	Monochromator Motor Mount
T04	Thermistor VR5	Carousel Tray 8	T20	VUV	Main Support Bracket
T05	Thermistor VR6	Carousel Wheel 8	T21	TIS #1	Green LASER (532 nm)
T06	Thermistor VR7	Carousel Tray 1	T22	TIS #2	IR LASER (1064 nm)
T07	Thermistor VR8	Carousel Wheel 1	T23	AO	AO Motor Mount
T08	Emissivity Plate #1	E-Plate	T24	DACS	DACS Mounting Flange
T09	Emissivity Plate #2	E-Plate	T25	PSC	PSC Top Cover
T10	Emissivity Plate #3	E-Plate	T26	PAC	PAC Top Cover
T11	Emissivity Plate #4	E-Plate	T27	TQCM	TQCM Mounting Plate
T12	Carousel Motor #1	Carousel Motor	T28	Enc. Base Plate	Base Plate
T13	Carousel Motor #2	Carousel Motor	T29	Enc. Side Panel Left	Left Side Panel
T14	Encl. Top Cover #1	Top Cover Top Rib	T30	Enc. Side Panel Right	Right Side Panel
T15	Encl. Top Cover #2	Top Cover Front Rib			

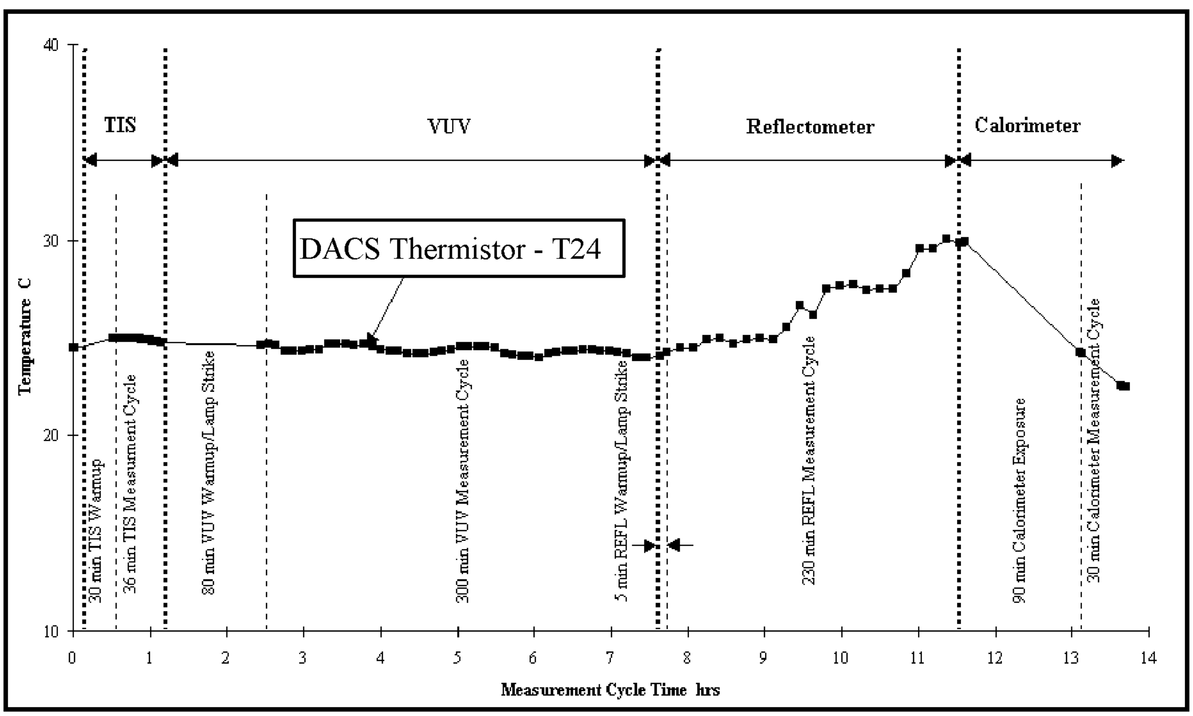

Figure 5: Nominal OPM Measurement Cycle Timeline.

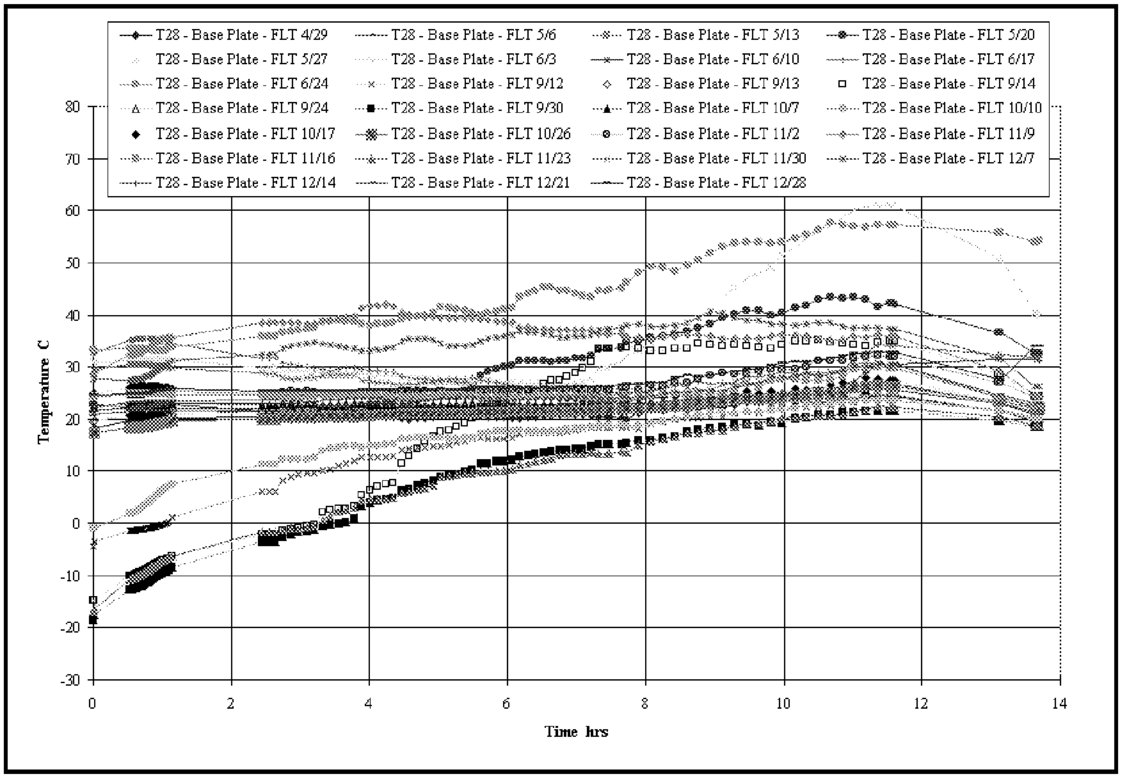

Figure 6: OPM Measurement Cycle Flight Data for Base Plate Thermistor (T28)

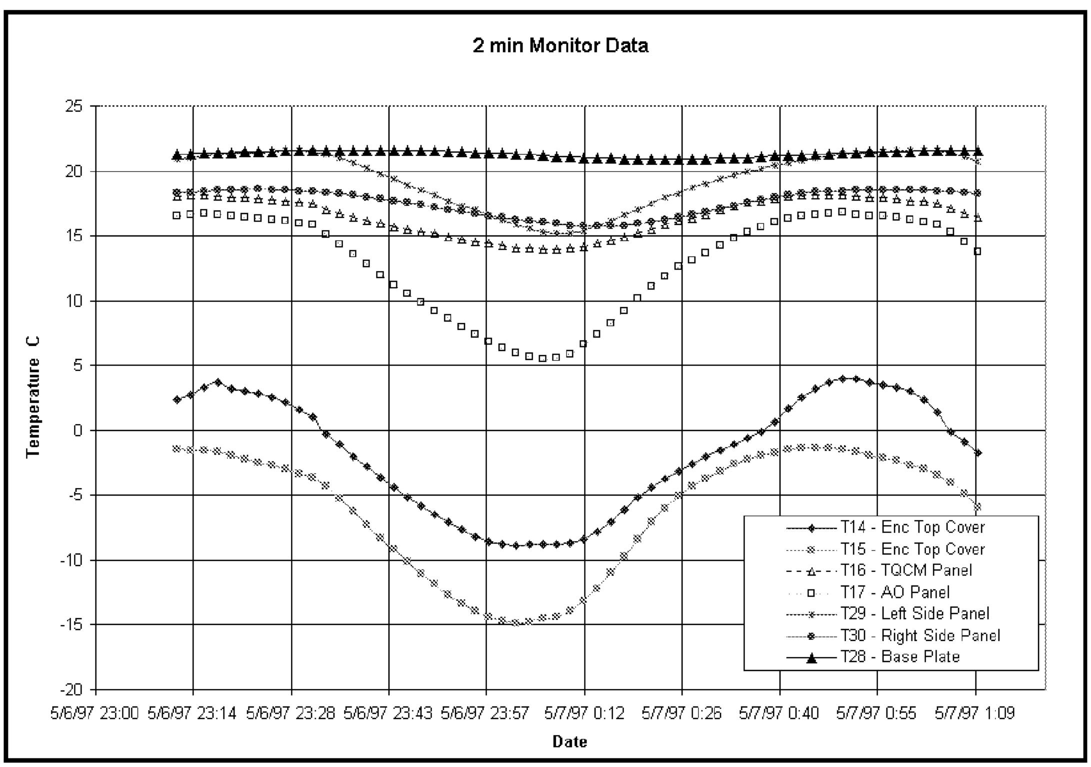

Figure 7: Example of OPM Two-Minute Monitor Data.

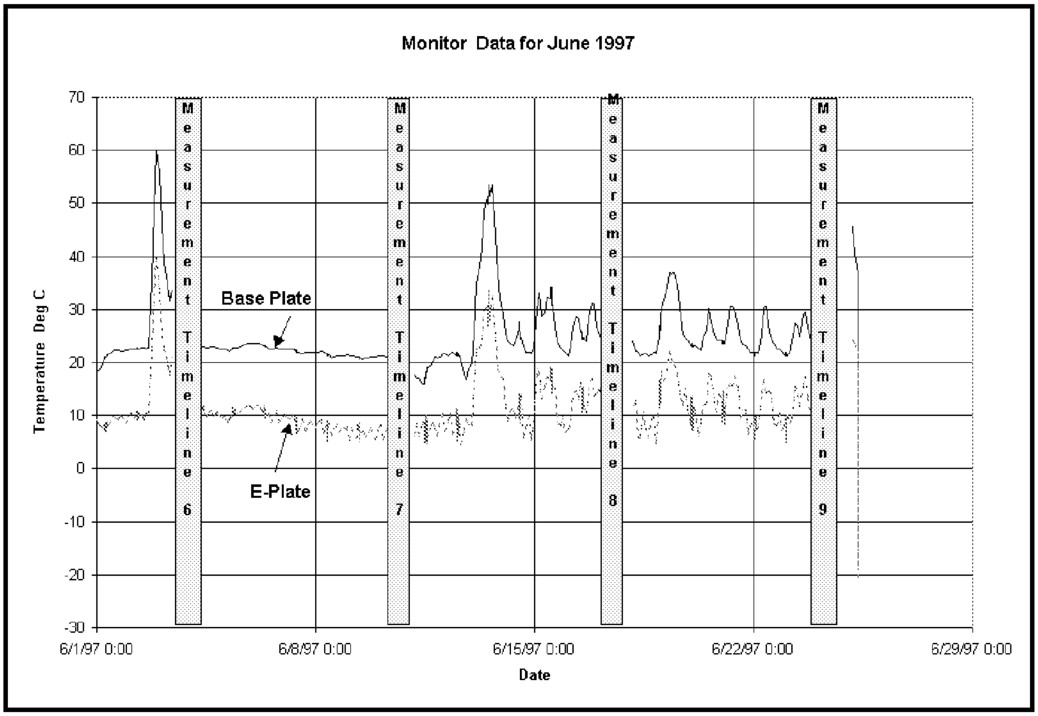

Figure 8: OPM Temperature Monitor Data for June 1997

OPM THERMAL VACUUM TEST

The OPM was designed for passive thermal control with supplemental active resistance heating to maintain an internal thermal environment between 0 and 40°C. The anticipated and documented Mir attitude orientation was gravity gradient for seventy to eighty percent of the time. To simulate this environment, the OPM was placed in a thermal vacuum chamber. Heat lamps were used to simulate the incident solar energy on the OPM. Based on thermal analyses for the OPM mounted on the Mir Docking Module, minimum and maximum operating temperatures were predicted for the "mission." These thermal set points corresponded to OPM Base Plate temperatures of -5 and +5°C at the beginning of a measurement cycle. Multiple thermal cycles were conducted while at vacuum with functional tests performed at the minimum and maximum set points. Figure 9 illustrates the OPM Thermal Vacuum Test Cycles. Figure 10 is the OPM in the thermal vacuum chamber.

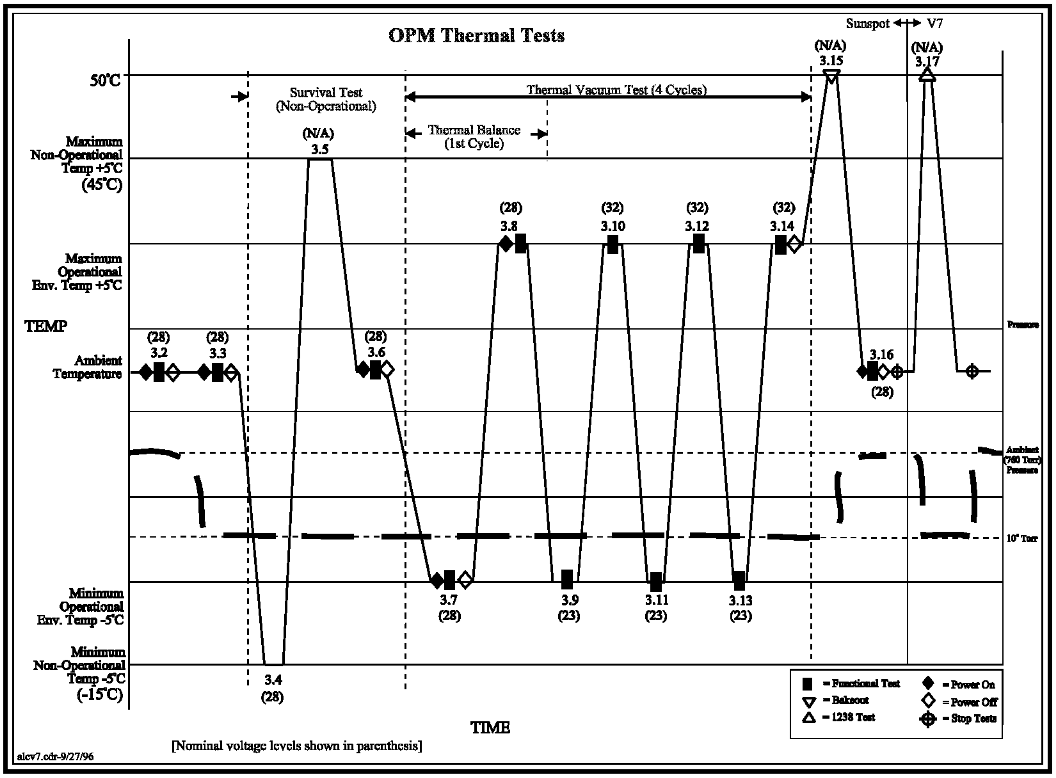

Figure 9: OPM Thermal Vacuum Test Cycles.

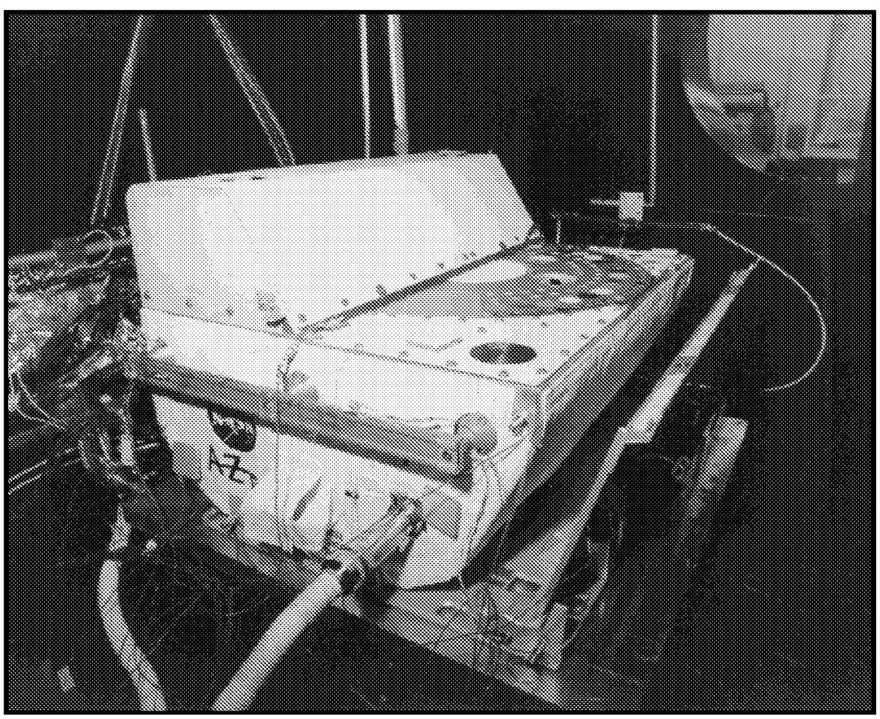

Figure 10: OPM in the Thermal Vacuum Chamber.

The thermal vacuum test began with a functional test at ambient pressure and temperature to ensure the OPM systems were setup and working properly. The chamber was evacuated to test pressure of at least $1x10^{-5}$ Torr (typically $3x10^{-6}$ Torr) and a second functional test conducted to check experiment operation at vacuum prior to beginning testing. The OPM was subjected to hot and cold survival temperatures, while non-operational, followed by a functional test at ambient temperature. Four thermal cycles were conducted, with the first concurrent with a thermal balance check to calibrate the thermal analyses to the actual hardware performance. Figure 11 is an example of the thermal balance temperature comparison between the thermistors located on the Reflectometer instrument and the OPM thermal models. The criterion for acceptable thermal balance was agreement within 5°C. The OPM proto-flight hardware successfully passed the thermal vacuum tests.

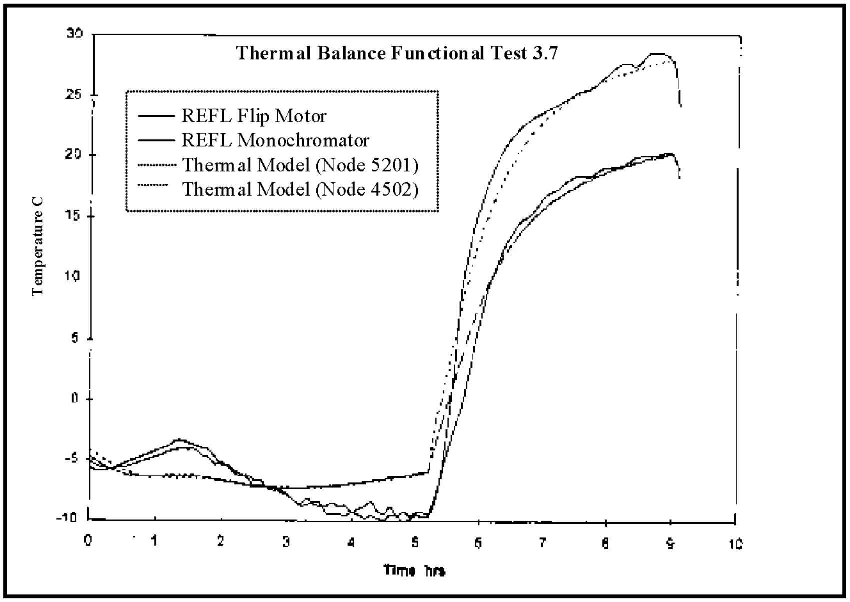

Figure 11: Thermal Balance Temperature Comparison for OPM Reflectometer Instrument.

OPM MISSION THERMAL DATA

For most space systems the primary purpose for development of thermal models is as a design tool. However, as the OPM program demonstrates, the thermal models in conjunction with flight temperature data can be extremely useful tools for evaluating the system performance and health.

One of the primary features of the OPM thermal control system is the use of Kapton-backed etched-foil electric heaters to maintain temperatures above the minimum limit temperature of 0°C. Figure 12 shows a typical temperature profile for the emissivity plate during two cycles of heaters "On" and "Off." The OPM heater "On" set point is 6500Ω that converts to 4.2°C. The OPM heater "Off" set point is 6000Ω which converts to 6.7°C. Note that the average of the emissivity plate thermistors T08 and T09 are used for controlling the heaters. The Figure 12 data is used as evidence that the heater system functioned within the design criteria.

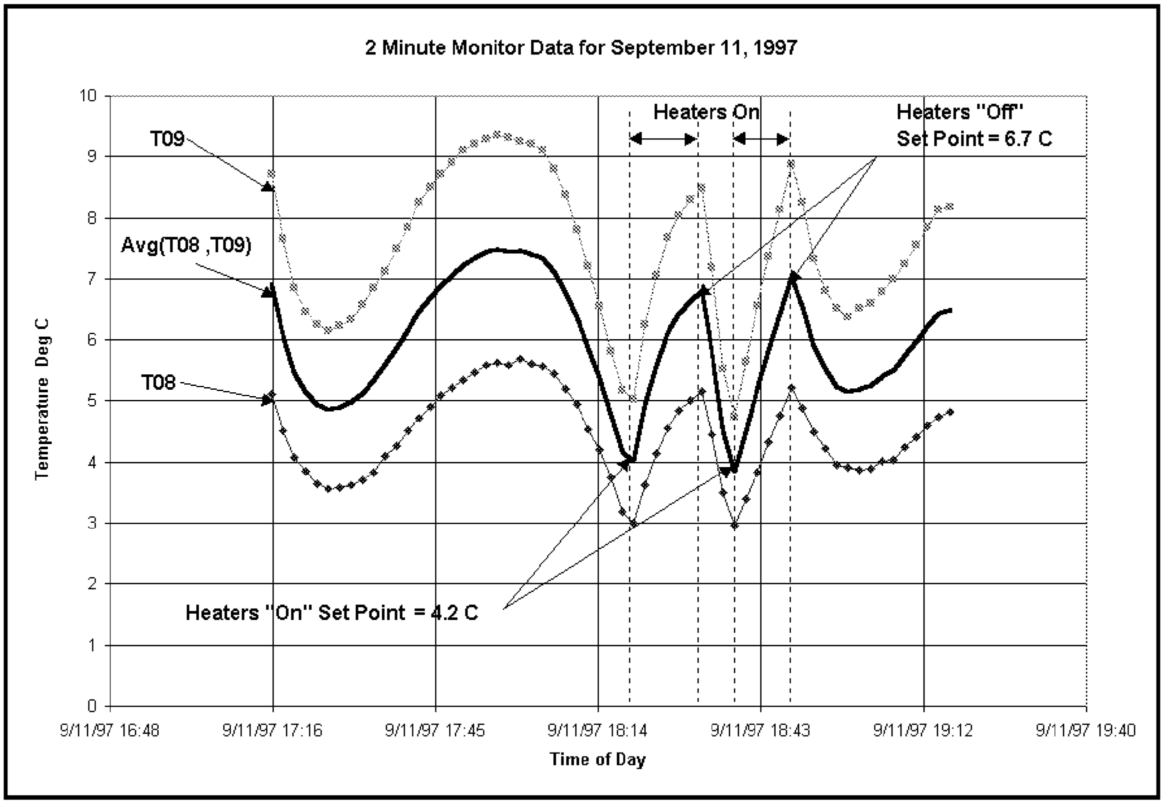

Figure 12: Typical OPM Heater Thermal Performance

In addition to evaluating specific components of the thermal control system, like the heater elements, the thermal data obtained from the OPM flight has been used to characterize the overall thermal performance of the OPM Thermal Control System. Figure 13 is an example of the temperature monitor data for the month of May, 1997. During this first month of deployment the system temperatures, represented by the base plate and emissivity plate thermistor data, was maintained between design limits (0-40°C). Figure 8, which summarizes the monitor data for June, shows the base plate temperature exceeds 40°C on June 3rd.

The thermal event on June 3 resulted in an anomaly investigation of the orbital attitude of the Mir space station. Figure 14 is an example of how the OPM thermal data was used to characterize the orbital attitude effects on OPM System temperatures. The 38 °C rise in base plate temperature on June 3rd is directly related to the attitude change of Mir. In this example the solar vector changed from 120 degrees from vertical, which is 30 degrees below the plane of the OPM sample carousel, to 25 degrees from vertical. In addition, this thermal event occurs during the four day period from June 3rd to June 7th during which the Mir orbit is 100 percent in the Sun (no Earth shadow). This set of orbital conditions describes the worst case hot orbital environment experienced by OPM. The preflight Mir attitudes used for design of OPM were Mir X-axis gravity gradient (70%), Mir X-axis solar inertial (20%) and undefined (10%). Since this attitude falls within the 10% undefined, the OPM design criteria was to maintain system temperatures below the maximum limit temperature (40°C) for a duration of 2.4 hours (10% of 1 day). The OPM base plate temperature after 2.4 hours is approximately 35°C which is below the design limit (40°C). The actual Mir attitude change lasted for 7.6 hours which exceeds the preflight design criteria and results in base plate temperatures of 60°C. Although the OPM base plate temperatures exceeded the design criteria on eight occasions (6/2, 6/13, 6/24, 11/3, 11/4, 11/27, 12/25, and 12/26) during monitoring mode and on three occasions (5/20, 6/3, and 6/24) during measurement cycles the only known temperature/external environment related failures of OPM hardware during the Mir mission is the radiometer sensor which failed on June 3rd.

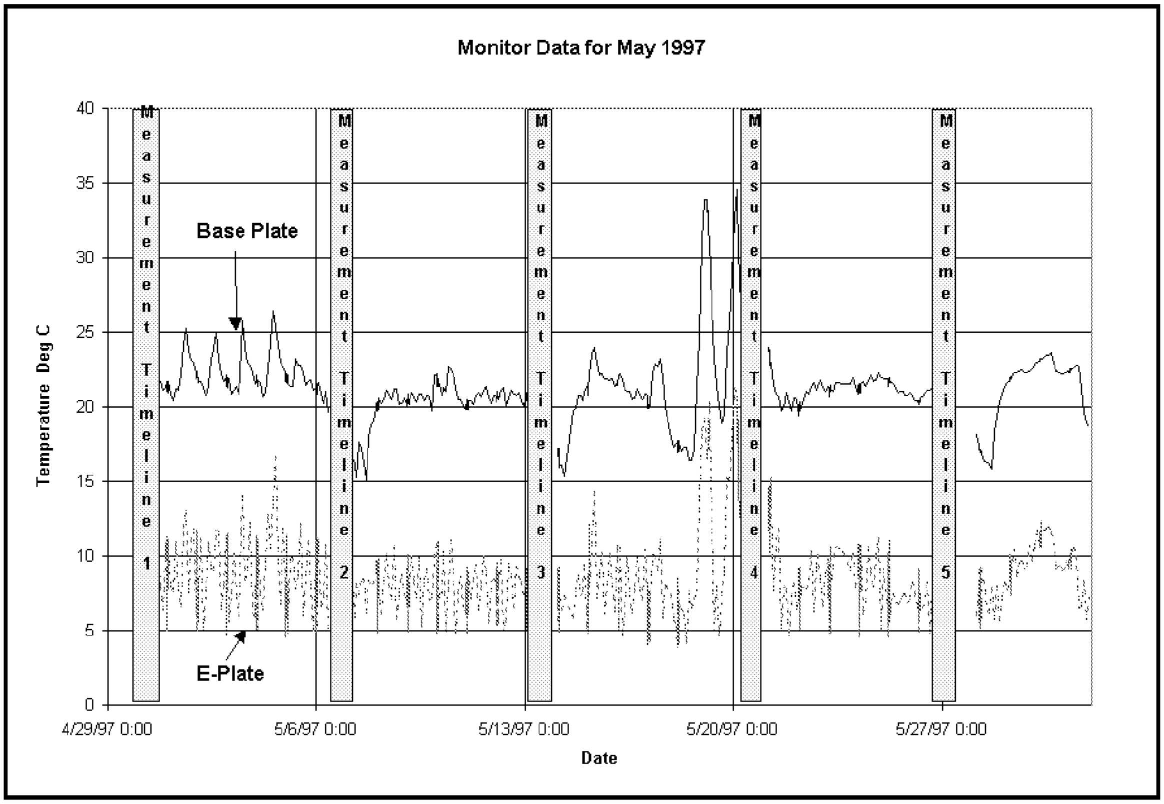

Figure 13: OPM Temperature Monitor Data for May 1997

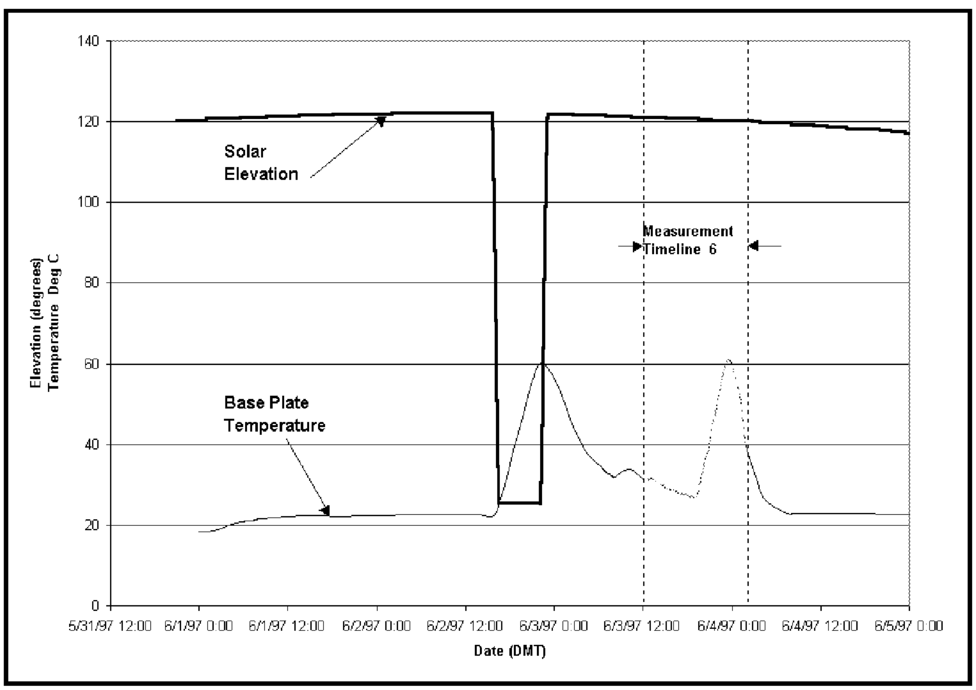

Figure 14: OPM Thermal Response to Mir Attitude Change on June 2, 1997

The first significant mission anomaly was the failure of the VUV instrument. The first indication of an anomaly with the VUV instrument occurred upon review of the first data transfer from Mir on April 30, 1997. This first data set included raw data from the measurement timeline which occurred on April 29. Included in this data were the raw data from the VUV instrument. This data was not within the expected measurement range. Immediately a fault analysis, and fault analysis tree were performed to determine possible causes for failure and possible courses of action for correcting the problem. The resulting fault tree resulted in a large number of possible causes for failure including bad detectors, VUV lamp sources, carousel position, data management software, etc. No direct evidence of the cause of the VUV failure was available real time during the mission. Visual inspection was the only methodology for evaluating many of the possible failure modes. However, the thermal data proved to be a very convincing indirect source of evidence pointing at the Deuterium Lamp as the most probably cause for failure.

Figure 15 is a comparison of the OPM April 29th Flight Data Thermistor T20 with parametric temperature profiles generated using the OPM SINDA thermal math model. Three parametric models were generated using SINDA. The first model assumes that the VUV was fully functional (20W lamp, 10W lamp heater and 4.5W stepper motors), the second model assumes that the lamp was not functional (10W lamp heater and 4.5W stepper motors), the third option assumes that both the lamp and the lamp heater are not functional (4.5W stepper motors). The model with both the lamp and lamp heater not functional shows excellent agreement with the flight data. This data was included in the VUV anomaly fault analysis which was performed during the OPM mission prior to retrieval. This thermal evidence was one of the key factors that identified the lamp as the most probable cause of the VUV anomaly. Post flight inspection of the OPM VUV confirmed that the lamp did not function due to a broken lamp heater element.

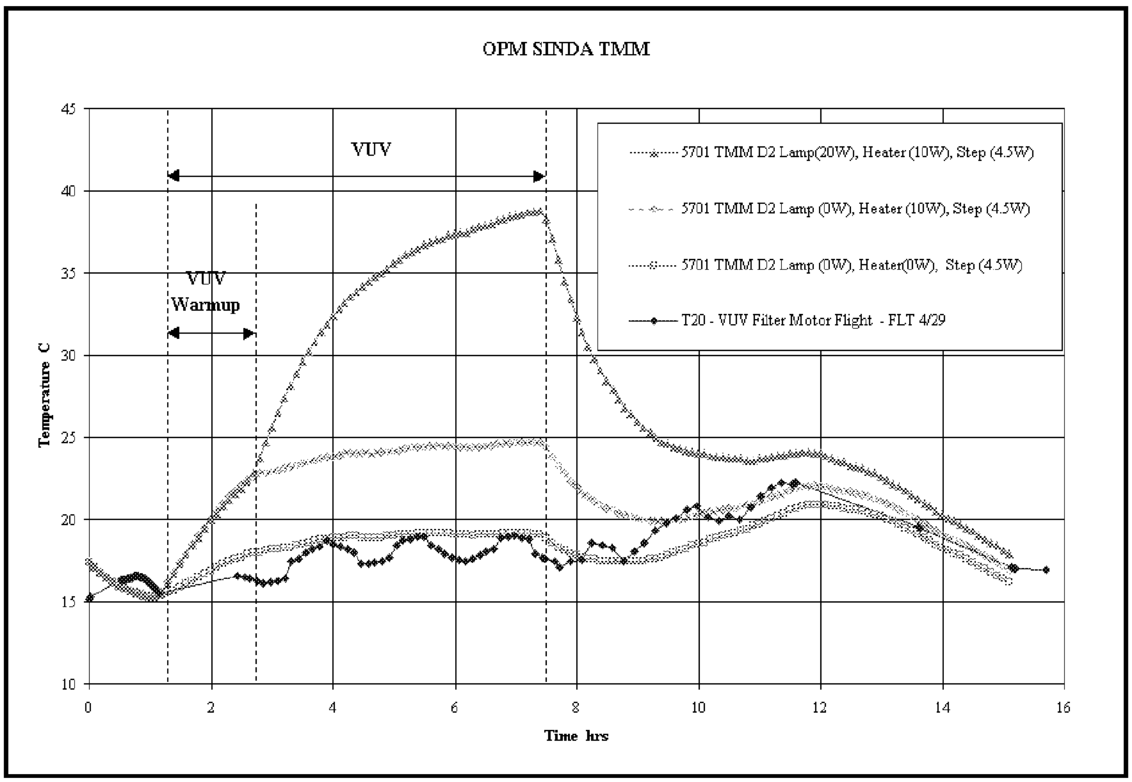

Figure 15: Typical VUV Thermal Profile.

The other major OPM mission anomaly was the loss of Mir power. This anomaly affected OPM in two significant ways. The first is the loss of power to OPM itself. The second is the resulting reduction in attitude control of Mir which continued to occur throughout the remainder of the OPM Mir mission.

The OPM experiment was flown on Mir without a real time clock. Mission elapsed time was recorded using an elapsed time clock. The result is that significant errors between the mission elapsed time and real time were produced during each of the OPM power losses. The most significant of these power losses resulted from the Progress collision with Spektr on June 25th. The collision occurred on June 25, 1997 on the Mir Station while practicing manual rendezvous procedures. Upon collision, the crew reacted quickly to seal off the leaking Spektr module and to conserve power. The OPM power was then severed in order to conserve battery power. The power remained off until September 12, 1997, when the OPM was officially repowered. Later, the OPM Team discovered the OPM power was not shut down by turning the power breaker to the "Off" position in the Docking Module and/or in the Krystal module. Instead, once the Krystal module was repowered, the power to OPM began cycling. In fact, the OPM experiment was powered up when the Mir Station entered the sunlight, and went off (unpowered) when it went beyond the terminator. When this was realized, the OPM was powered down at the power breaker until ready for official power up. Figure 16 shows the estimated power on/off status chart for the period between September 12 and October 12, 1997. The OPM did not have a real-time clock, only an elapsed timer so the exact times cannot be determined. The time is given in Decreed Moscow Time (DMT) - the time used by the Mir crew.

The OPM temperature data combined with the Mir attitude data (Figure 17) and the OPM "ON" timeline (Figure 16) obtained from the Mir daily activity reports has been used to adjust the OPM mission elapsed time to a best estimate of real time. Table 2 summarizes the correction factors which have been applied to the mission elapsed time beginning with the powering "ON" of OPM on September 9, 1997. No correction has been applied to the period between September 9 and 15 due to a lack of significant Mir attitude events or accurate OPM Power status information. Figure 18 is an example of how the OPM base plate responded to Mir attitude changes on November 6 - 11, 1997. This data incorporates the seven-hour correction to the timeline as shown in Table 2. Note that "loss of power" is an anomaly that was beyond the scope of the OPM mission. The OPM design was shown to be capable of fully recovering from this condition. Sufficient thermal data was recorded to allow a reconstruction of the mission timeline within the accuracy of the 2-hour monitoring data. No science data was lost or rendered unusable due to the inaccuracy of the reconstructed mission timeline.

The OPM experiment lost Mir power on several occasions after the June 25th collision. On at least six occasions the OPM was restarted from a "Cold Soak" condition (Base Plate below -10°C). Four of the restarts were immediately followed by an OPM measurement cycle (9/12, 9/14, 9/24, and 11/23). Two of the restarts occurred during monitoring mode (~9/9 and 10/21). Figure 19 shows the rate at which the OPM recovers to nominal temperatures after a cold restart on October 21, 1997. Both the base plate and the emissivity plate are above 0°C within five hours of restart. Note that "loss of power" is an anomaly which was beyond the scope of the OPM mission. However, the OPM design was shown to be fully capable of recovering from this condition.

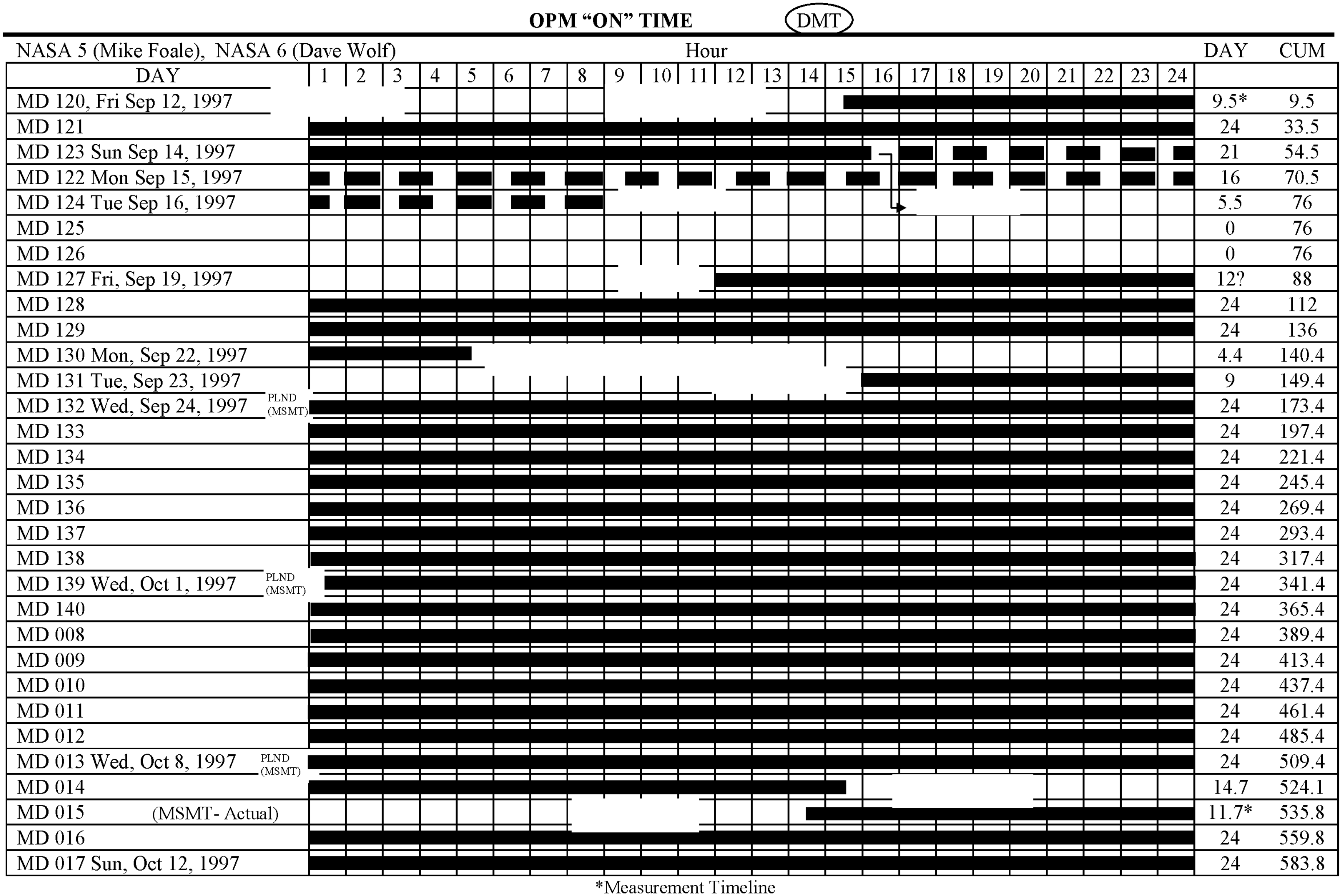

Figure 16: OPM "ON" TIME - Measurement Timeline

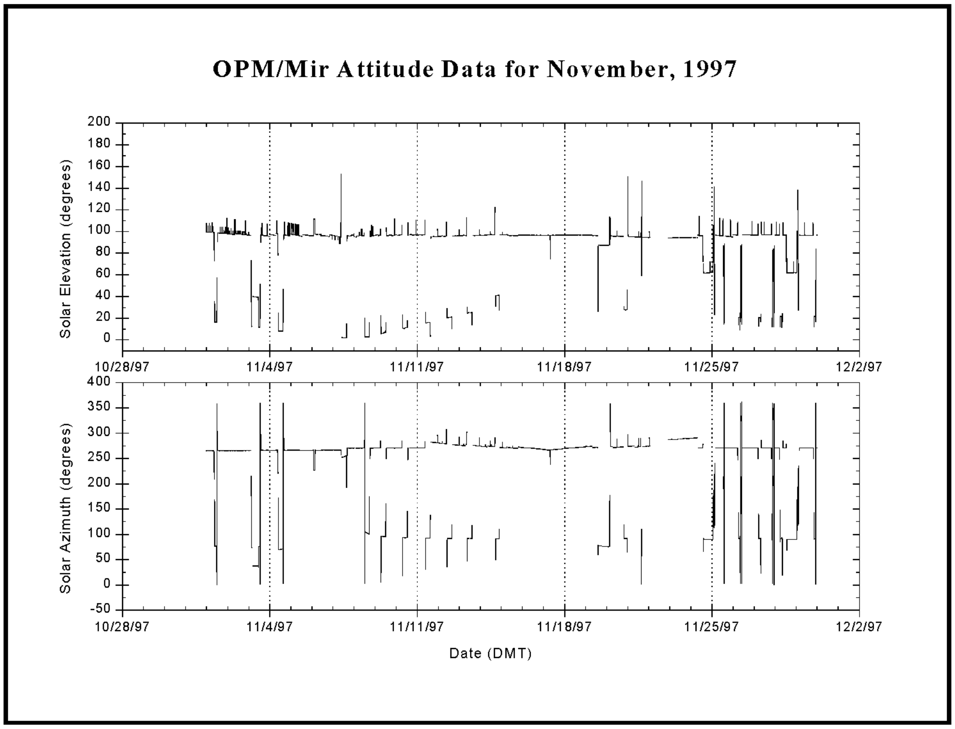

Figure 17: OPM/Mir Attitude Data for November, 1997.

Table 2: OPM Mission Elapsed Time Correction.

MET		Correction	Corrected Timeline	
Start	End	hrs:min:sec	Start	End
9/9/97 17:15	9/15/97 17:18	0:00:00	9/9/97 17:15	9/15/97 17:18
9/22/97 1:41	9/22/97 3:41	56:00:00	9/24/97 9:41	9/24/97 11:41
9/23/97 1:10	9/28/97 23:18	36:00:00	9/24/97 13:10	9/30/97 11:18
10/1/97 0:18	10/10/97 1:37	-10:53:00	9/30/97 13:25	10/9/97 14:44
10/10/97 21:05	10/19/97 15:13	14:00:00	10/11/97 11:05	10/20/97 5:13
10/19/97 15:13	10/20/97 23:15	56:22:00	10/21/97 23:35	10/23/97 7:37
10/23/97 1:16	10/24/97 21:33	8:22:00	10/23/97 9:38	10/25/97 5:55
10/25/97 11:33	11/21/97 18:03	7:00:00	10/25/97 18:33	11/22/97 1:03
11/22/97 11:55	12/31/97 15:22	42:23:00	11/24/97 6:18	1/2/98 9:45

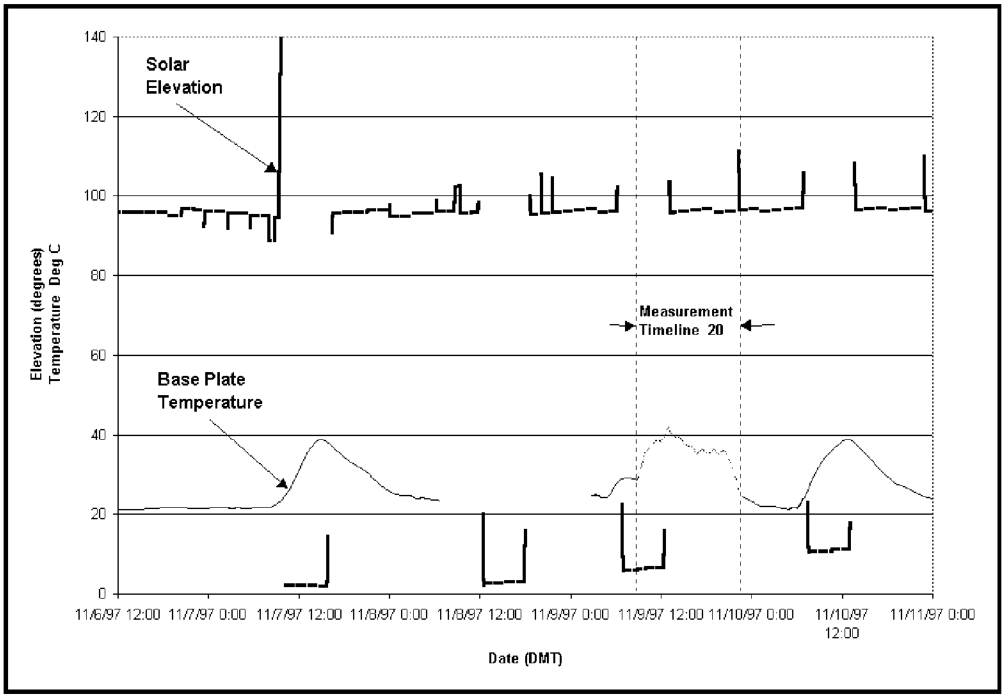

Figure 18: OPM Thermal Response to Mir Attitude change on November 6-11, 1997.

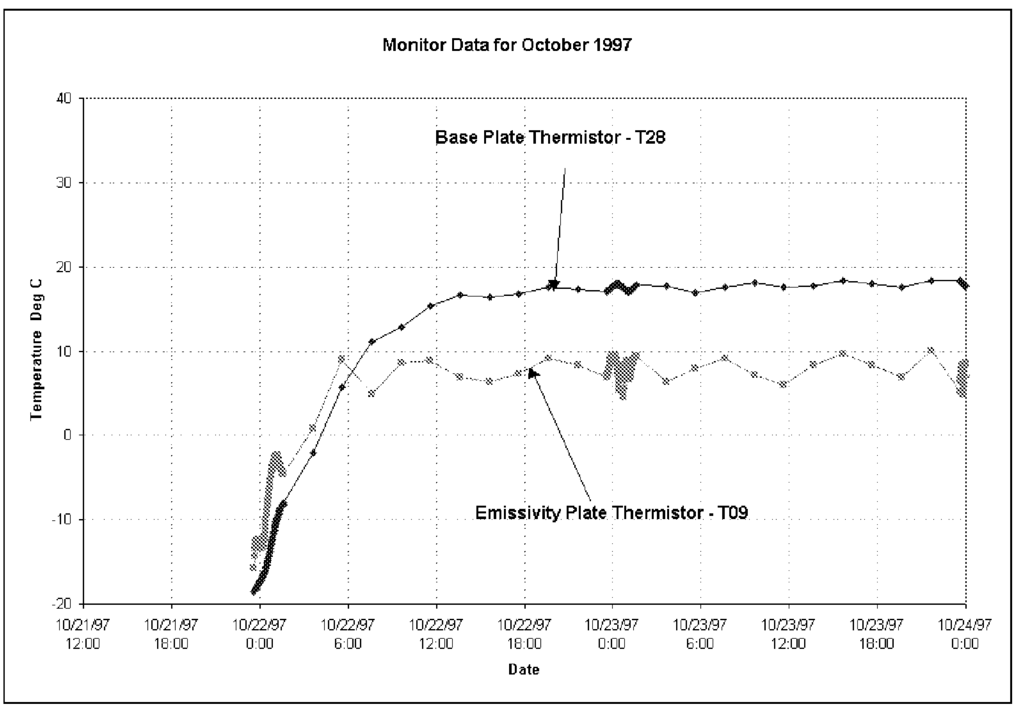

Figure 19: OPM Restart Temperature Response on October 21, 1997.

SUMMARY AND CONCLUSIONS

A thermal control system was designed for the OPM Experiment. Detailed SINDA and TRASYS models were developed for the OPM which were used to evaluate system health and performance. Thermal flight data and thermal analysis techniques were demonstrated to be critical sources of information in the evaluation of flight anomalies.

ACKNOWLEDGEMENTS

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