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Abstract

Infrared environmental simulation has been developed into a routine operation at the Jet Propulsion Laboratory. Tungsten filament quartz lamps are used in arrays that provide the desired environmental stimulus. These arrays are capable of producing high heat fluxes over large areas. The uniformity of the resulting flux, the dependency of the spectral distribution on the applied voltage, and the aspects of controlling the resulting configuration are important considerations for an infrared simulation, This paper reports on the approach that was taken at JPL, to provide a solution to the unique challenges of infrared simulation. A fast flux mapping technique, using an infrared camera, is described and an example of a measured flux uniformity is given. The function and use of calorimeters for absorbed flux measurements and the computer control of the test environment are documented. Together, these techniques have evolved into an integrated, flexible and readily available thermal test environment.

Introduction

The costliness of conventional thermal vacuum testing is well known and has been the driving force behind efforts to develop a cost effective alternative. In recent years infrared simulation techniques have proven to be a viable approach, e.g., a representative review[1] provides the Canadian Space Agency's rationale for infrared simulation.

The tungsten filament lamps that are used as heat sources can produce flux levels that are equivalent to several solar constants, and, depending on the configurational arrangement of these lamps, highly uniform flux distributions can be achieved over large areas. These are features that typically are found only in large and costly solar simulators.

But the use of quartz lamps has its own idiosyncrasies. Notably, the words "infrared simulation" are misleading in this context. It is a customary convention in spacecraft thermal control to refer to radiation below about 3 μm as "solar" and anything above as "infrared", thus providing well defined boundaries for optical properties. The spectrum of a quartz lamp falls on both sides of this division and furthermore changes with the applied voltage and filament temperatures which leads to analytical difficulties. This circumstance led to the development of calorimeters for the use in thermal vacuum testing. Calorimeters measure the absorbed flux, eliminating the need of complex calculations.

Because calorimeters make spot measurements it is necessary to demonstrate reasonable uniformity of the actual flux distribution in order for the spot measurement to be representative. This was in fact the first problem that was recognized and solved at JPL by means of a flux mapping technique[2] utilizing an infrared camera. Fast flux maps allowed quick adjustments to lamp array geometry, resulting in the desired uniformity.

This paper discusses the advantages and disadvantages of infrared simulation and the various techniques that were developed at JPL.

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*Technical Group Leader

Review

The integration of IR simulation techniques into a routinely used test environment has evolved for some years at JPL. The first test involving lamp arrays was the MAGELLAN solar panel test in 1988. Power sources were controlled by a combination of manually adjusted Variac's and a commercially available automated controller. This test demonstrated the capability to impose high heat loads over large areas, but, the control left a lot to be desired,

Testing of the MIS (Microwave Limb Sounder) instrument, followed in 1989. This effort, including a thermal balance test and calibration, introduced calorimeters into the test configuration. Control was provided by an improved application of the same controller used for the Magellan solar panel test. In preparation for the MLS test the flux mapping technique[2] was developed. This technique has been subsequently utilized in many different applications, including the determination of the spatial energy distribution in a laser beam and a recent application for the MSTI project,

The TOPEX (Ocean Topography Experiment) solar panel qualification, consisting of 250 temperature cycles, and the subsequent acceptance testing of four flight panels was concluded in 1990. In preparation for these tests the previously used controller was replaced by a data acquisition and control unit that was developed in-house, The software was selected from commercial y available packages, This test demonstrated wide flexibility in power handling and control capabilities, Due to the large size of the TOPEX solar panels, approaching 9 m^2, and because two panels were tested simultaneously, nearly 350 kw of power were installed in the vacuum chamber. Each lamp array consisted of six individually controlled zones, four along the perimeter and two interleaving zones in the center. This configuration allowed the control of temperatures to a uniformity of better than 10°C. In addition the panel rate of temperature change was precisely controlled during cycling and front-to-back gradient requirements were maintained. Figure 1 below shows the test configuration. One of the two solar panels can be seen sandwiched between two lamp arrays.

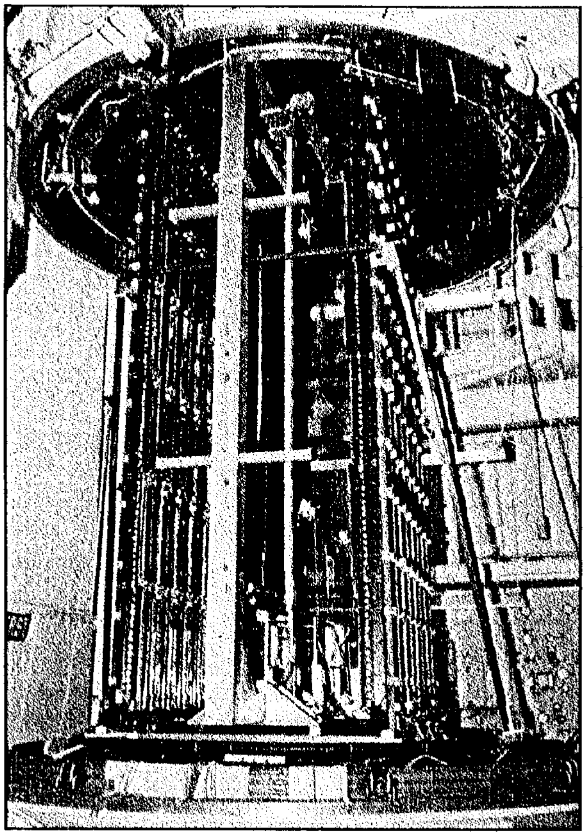

Figure 1. The TOPEX Solar Panel Test Configuration

In 1992 the test software was extensivel y reworked and throughout 1993 seven NSCAT (NASA Scatterometer) antennas were qualified, thermal balance and flight acceptance tested. In the same year the NSCAT electronic units were thermal balance tested and calibrated using infrared simulation. Subsequently the simulation system has been repeatedl y used in JPL's Spacecraft Assembly Facility for continued evaluation of the NSCAT instrument, in atmosphere at controlled temperature levels.

In its latest application the system was used for a CASSINI thermal test.

Tradeoffs

A system of quartz lamps for infrared simulation is not necessarily the optimum choice for a given set of thermal test requirements. Traditionally a large number of options exist to control temperatures, These options include surface mounted heaters, heater controlled panels or targets, GN_2 heat exchangers, chamber shrouds and solar simulation.

An infrared simulation employing quartz lamps is no substitute for solar simulation. If the spectral sensitivity of surfaces or the effects of a collimated beam are essential to meeting the test objectives, then there is no alternative to solar simulation. However, if solar simulation is considered because of a convenient] y available heat source, then a review of the associated costs will in almost all cases result in favor of alternatives to solar simulation.

1 disadvantages

The need of flux uniformity typically leads to the use of more lamps than the actual heating power requirement dictates. As a result, there is a potential for fast overheating of the test article in an anomalous situation, Many large power supplies are needed and it may be necessary to use 480 volt 3-phase power which can be an unacceptable electro magnetic noise source that disturbs other measurements or calibrations of the test article.

Quartz lamps are line sources. For flux uniformity reasons the minimum distance between lamps and the target surface is about 0.25 m. 1,amp arrays are heavier than heated sheet metal surfaces and if possible should not be installed above the test article to prevent damage from lamps breaking during the test. Therefore, an infrared simulation configuration requires space, reduces the available volume for the test article and may impose constraints on the test configuration. The alternative is to test in a larger chamber, but increasing chamber size typically translates into increased test cost.

A substantial initial investment of resources is required to design an infrared simulation system. The key contributors to costs are control software and hard ware, power supplies and labor for design, test and integration of the system. An additional significant cost factor is the infrared camera that is used at JPL for flux mapping.

Advantages

Infrared simulation is a non-contact method of applying heat to a surface, A non-contact method is in many cases the only way to control temperatures. Examples are optical surfaces, antennas and solar arrays.

High flux levels can be imposed over large areas, Levels equivalent to three solar constants or more can easily be achieved. Flight qualification of solar panels is a good example of a requirement for higher flux levels over large areas.

Heating can be applied nearly instantaneously because of the fast response time of lamps. This is an important feature if, for example, the transient effects of sudden solar illumination have to be simulated. Again solar panels serve as a good example.

The overall blockage of view by a lamp array is about 15%. In a configuration where lamps are placed between cold walls and the test article cooling by radiation is barely impeded, An optimized cooling capability provides for more realistic space environmental simulation and shortens test time for cyclic testing. Test time is a significant driver of overall test cost.

The use of calorimeters, as implemented at JPL, makes it possible to directly use analytically determined heat flux values for environmental control. Traditionally, test environments are characterized and controlled in terms of temperatures that are derived from environmental fluxes. The benefit of eliminating the need of complex calculations of control parameters derived from flux values can be readily appreciated.

Elements of Infrared Simulation

The elements that are used in JPL's infrared simulation are described in the following together with their integration into the simulation system.

Quartz Lamps

A typical quartz lamp consists of a tungsten filament, enclosed in a quartz envelope. The diameter is approximately 1 cm and the length can vary. The lamps used at JPL are about 64 cm long and are capable of producing 40 watt/cm at the rated voltage, Higher voltage and power output are possible, but the life time will be reduced. The geometry of the lamp results in a line source for heating. This has a direct relation to the design of lamp arrays. Some lamps must be operated in the horizontal position, however, designs for vertical operation are available,

The lamp resistance at ambient temperatures is about 7 Ω. This resistance can vary over two orders of magnitude depending on the temperature of the filament. Obviously, this needs to be considered when designing the electrical circuit. Furthermore, the inrush current, when lamps are first turned on, will be at least 10 times the normal operating current. These conditions result in the need for power supplies with high voltage and current capabilities, The power supplies currently used at JPL are SCR's (Silicon Controlled Rectifiers). A start-up problem associated with high initial currents occurs when lamps are first turned on after soaking in a cold environment in the off condition. It is helpful to initially ramp lamp power up very gently to avoid tripping of circuit breakers.

The emitted energy is distributed over a spectral range starting at about 0.3 pm. The spectral region where most of the energy is emitted changes with the applied voltage, see figure 2. This behavior is of no concern if a test article is to be controlled to a specified temperature. The spectral characteristic of quartz lamps becomes important if the amount of heat absorbed by the test article is to be controlled. The absorbed amount of energy is a function of the spectral distribution of the energy source and in this case a function of the applied voltage.

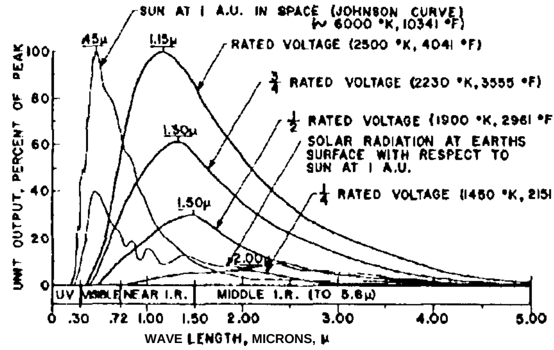

Figure 2. Spectral Output of Tungsten Lamps

Calorimeters

The approach taken at JPL is to use calorimeters[3] to actually measure the amount of energy absorbed by the test article rather then trying to analytically model the radiative heat exchange and predict required lamp voltages. The calorimeter is a simple device, approximately 3.5 cm in diameter, that consists of a sample disc mounted in a cup-like enclosure and thermally isolated from it. The exterior of the sample disc is covered with the same material as the actual test article surface, A temperature sensor on the inside of the sample disc measure the temperature which can be correlated to the amount of absorbed energy. A schematic of a typical calorimeter is shown below in figure 3.

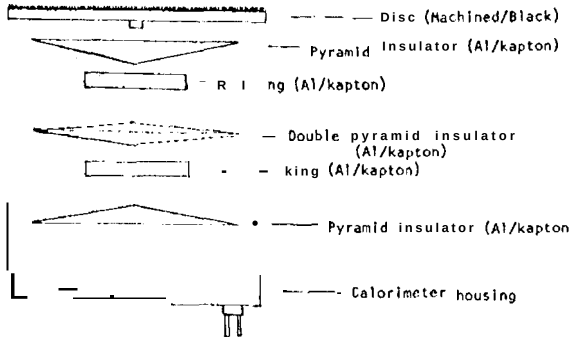

Figure 3. Calorimeter Schematic

The calorimeter is calibrated by applying a known amount of heat to the sample disc. An energy balance correlates the disc temperature to the heat input and the housing temperature. The construction of the calorimeter is uncomplicated so that an analytical model of the calorimeter consists of only two nodes plus an external radiation sink. One linear and one radiation conductor are sufficient to account for heat exchange between cup and sample disc, The entire correlation process is completed in very short time by a personal computer.

The calibration data are obtained in a thermal vacuum environment. The most recent calibration method consists of a black body cavity designed and build at JPL that can be controlled from -180°C to 150°C. The calorimeter disc views the cavity interior and is allowed to stabilize at different cavity temperatures. A full set of calibration data is obtained in about two days,

Calorimeter discs are small and respond relatively fast to changes in thermal environments, but their stabilization time is not fast enough to monitor transient behavior, e.g. a low earth orbital simulation, accurately. The latest experimental calorimeter design at JPL has been greatly improved and an example of the response is shown in figure 4.

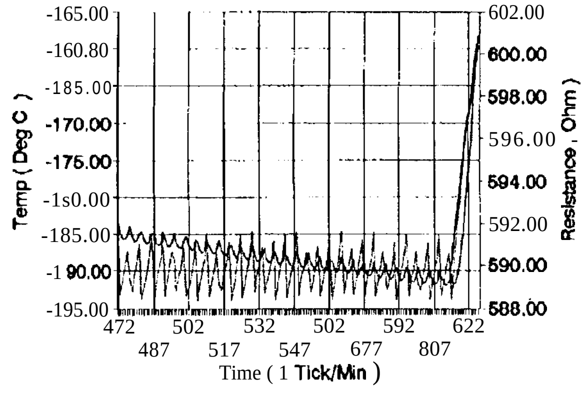

Figure 4. Calorimeter Response

The curve with the larger excursion is the actual black body cavity temperature. The curve with the smaller excursion is the measured sample disc temperature sensor resistance. The lag of the sample disk is reduced to about two minutes and the sensitivity at -190°C is better than 0.5 W/m^2.

Calorimeters are easily integrated into a test configuration and are currently used for closed loop flux control during thermal balance testing at JPL.

Lamp Arrays

Individual quartz lamps are integrated into arrays that cover the required area of illumination, The array size is typically larger than the target area to offset edge effects, A support, frame holds elements of two lamps which constitute the basic building block. The modularity of the design permits fast configuration changes. The interchangeability of the basic module allows for quick replacement of broken units.

Each module includes a planar reflector between the lamp and the support structure, The reflector redirects energy towards the target and improves the flux uniformity. The reflector surface also protects support structure or other nearby surfaces from overheating,

The initial design of the basic unit incorporated adjustments of the reflector width and the distance between reflector and lamp. These dimensions were adjusted until a satisfactory flux distribution was measured. The large TOPEX lamp arrays include this design feature. Later designs are based on the experience gained from the first arrays. The current design does not include the early adjustment capability, significantly reducing the resources associated with lamp array fabrication.

Due to high voltages and currents special care must be given to electrical wiring. The JPL lamp array wiring uses bare copper wire to maximize cooling of I^2R losses, Ceramic isolators and careful routing of the bare wire are necessary to prevent arcing. It goes without saying that caution is required for any pre-test checkouts.

Flux Mapping

Knowledge of the spatial distribution of the energy emitted by a lamp array is of paramount importance, Conventional measurements, including the approaches used at JPL, provide a spot measurement. These methods are not, sufficient to map a large lamp array, The time required, especially if the array geometry is iteratively changed based on real-time measurements, consumes resources that are typically limited from the beginning of any test activity.

A flux mapping technique[2] was developed at JPL that incorporates an imaging infrared radiometer. Figure 5 below shows the measurement configuration.

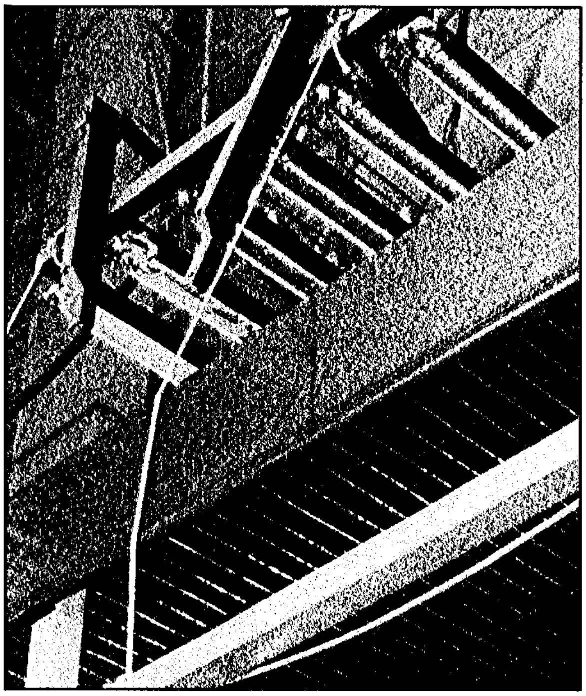

Figure 5. Flux Mapping Configuration

The lamp array is positioned above a very thin but opaque foil of black kapton at a distance identical to the actual test configuration. The energy emitted by the lamp array is absorbed by the foil and, due to the insignificant lateral conduction within the foil, leaves a temperature "imprint" that is similar to the absorbed flux distribution.

The imaging infrared camera records the entire temperature distribution instantaneously and stores it for evaluation, An energy balance, including a term for convection, correlates the measured temperature to the absorbed flux. A coarse assessment based on the false color temperature image is possible in real time. Detailed flux maps can be produced by postprocessing the stored images. Figure 6 shows the flux map of the TOPEX lamp array used for qualification testing.

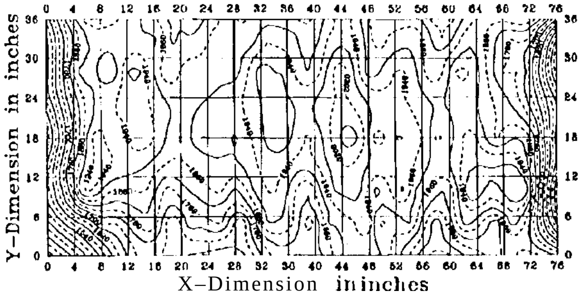

Figure 6. Flux Map, Units in W/m^2

Lines of constant flux are predominately aligned along the vertical direction. The reason for this is that the lamps were aligned in the same direction. The map dimension correspond to the qualification panel dimensions. It can be seen that reasonable uniformity is maintained all the way to the top and bottom edge of the panel. The left and right edge show a sharp drop in flux. Based on this initial map the lamp array design was augmented with lamps controlled individually on the left and right side of the panel. The result was a near isothermal temperature distribution in the solar panel during the test.

The relation of the flux distribution to the lamp array geometry is evident. One feature of this distribution warrants further discussion; figure 7 on the following page is provided for illustration. It can be seen that directly beneath the lamps the flux level drops considerably. The reason for this non-intuitive behavior is the blockage of reflected energy by the quartz envelop. Some energy emitted by the lamp filament is absorbed by the largely transparent quartz envelope and then reradiated at longer wavelengths, At these wavelength the quartz envelope is no longer transparent and the energy that is reflected by the reflector is blocked.

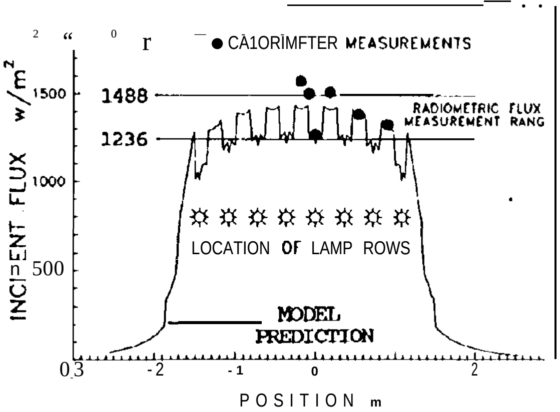

Figure 7. Details of Flux Distribution

The sharp dips represent the partial "shading" by the quartz envelopes, Awareness of this behavior is important when defining the location of calorimeters. If a calorimeter is placed directly underneath a lamp it will monitor flux values that can be significantly below the average flux level.

The other features in figure 7 correlate calculation and calorimetric measurements with the flux mapping technique. Reference 2 reports on these measurements in detail,

Control System

The test control system warrants a detailed discussion and is only introduced here. The control system functions as the nexus in the overall test control configuration. It's primary function is to provide closed loop control of fluxes and temperatures.

The control system design approach was to provide flexibility and modularity. To that extend the SCR power supplies are mounted in power distribution racks. Each rack contains two 208v/30amp single phase SCR's and one 480v/100amp 3-phase SCR. Each power distribution rack is self contained including circuit brakers, fuses and analog status indicators. All racks are interchangeable and can be quickly substituted in case of malfunction or failure,

The closed control loops are monitored by a PC based controller, This controller exhibits the same modularity and flexibility as found in the power distribution racks. A schematic overview is provided in figure 8.

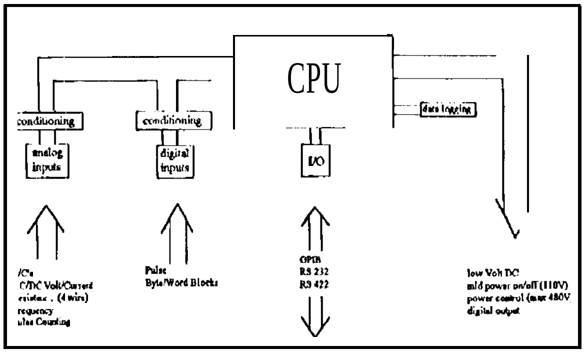

Figure 8. Control System

The control system can easily be configured through software, An ASCII input file is used to specify the desired configuration, In its applications to date the control system has been used with E-type and K-type thermocouple, (4-wire) resistance temperature sensors and calorimeters. The calorimeter thermal model resulting from the calibration was programmed into the controller and measurements of calorimeter disk and housing temperature were translated into flux data in real time, allowing use of the heat flux as the primary control parameter.

The control system includes many safety features, It monitors actual measurements against alarm values and reacts to alarm situations by assuming a pre-defined state. Safety features also include a vacuum interlock that shuts down high voltage during loss of vacuum to prevent corona discharge. The system can be controlled entirely by manual inputs in case of a computer problems, and it can be shut down completely at the push of a button during emergency situations.

The control system currently operates twelve independent loops. Each loop can follow its own timeline. Ramping and hold periods are easily defined in an ASCII input file by specifying target set point and duration for the desired transition. The software was initially written QuickBASIC, but currently is undergoing a transition to C++.

Environmental. Simulation Examples

Two examples that demonstrate the capabilities of infrared simulation are shown below. Figure 9 is an example extracted from the NSCAT thermal balance test. The absorbed flux was independently controlled for all three electronic unit radiators.

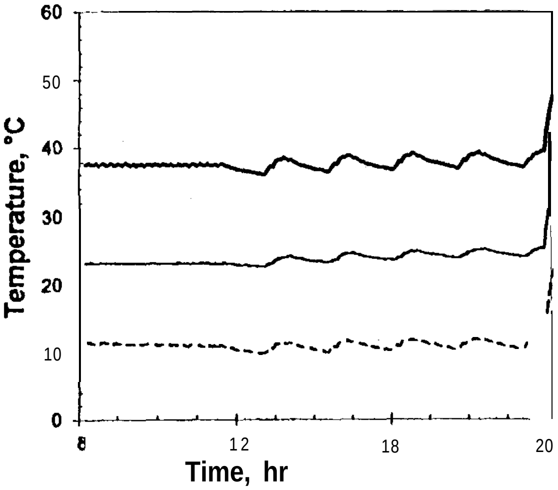

Figure 9, Flux Control During Thermal Balance Test

The temperatures of the three electronic units were completely unconstrained and represent the true response to the simulated environment. The first, stable, part of the curves represents the end of a stabilization period based on orbital average flux values. The cyclic part of the curves corresponds to an actual low earth orbital transient simulation that is follow by a simulated sun view. The entire sequence was pre-programmed and executed automatically.

The second example demonstrates the precision and repeatability of temperature control, The curves represent different temperatures in different locations of one of the NSCAT antennas during flight acceptance testing.

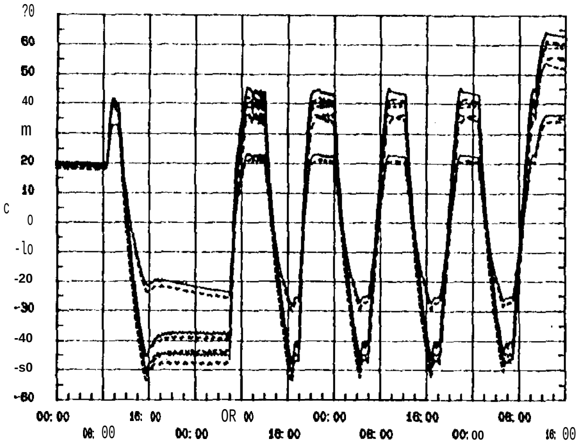

Figure 10. Temperature Control During Flight Acceptance Test

The temperature cycles consist of a fast transition over a wide temperature range followed by a stabilization. All four temperature cycles are virtually identical. This test sequence was also pre-programmed and executed automatically.

Conclusions

An infrared environmental simulation technique has been developed that has proven to be flexible, reliable, and cost effective in numerous tests.

The thermal design of the MLS electronic units and antenna system, and the MAGELLAN and TOPEX solar panels were verified using infrared simulation. All are now in orbit and their thermal performance has been excellent.

Tests typically can be accommodated with few modifications to the control system hardware and software and experienced support personnel is readily available.

Significant cost savings can be realized because of fast set-up times and reduced test duration due to precise environmental control. In times of limited funding this can bias a resource trade-off in favor of valuable testing.

Acknowledgements

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Credit is also due to Mr. R. Wargo for conceiving and building the control system and his unwavering support during countless nights of thermal vacuum testing.

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