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Thermal Verification Testing of Commercial Printed-Circuit Boards for Spaceflight

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SUMMARY AND CONCLUSIONS

This paper discusses a method developed to verify commercial printed-circuit boards for a shuttle orbital flight. The Space Acceleration Measurement System (SAMS) Project used this method first with great success. The test sequence is based on early fault detection, desire to test the final assembly, and integration with other verification testing. A component thermal screening test is performed first to force flaws in design, workmanship, parts, processes, and materials into observable failures. Then temperature definition tests are performed that consist of infrared scanning, thermal vacuum testing, and preliminary thermal operational testing. Only the engineering unit is used for temperature definition testing, but the preliminary thermal operational testing is performed on the flight unit after the temperature range has been defined. In the sequence of testing, vibration testing is performed next, but most vibration failures cannot be detected without subsequent temperature cycling. Finally, final assembly testing is performed to simulate a shuttle flight. An abbreviated thermal screening test is performed as a check after the vibration test, and then a complete thermal operational test is performed. The final assembly test finishes up with a burn-in of 100 hours of trouble-free operation. Verification is successful when all the components and final assemblies have passed each test satisfactorily. This method has been very successful in verifying that commercial printed-circuit boards will survive in the shuttle environment.

1. INTRODUCTION

Costs can be kept down when developing shuttle space experiments by using commercial printed-circuit boards whenever possible. These boards, of course, were designed to operate in a convective environment and not the nonconvective (microgravity) environment of an orbital flight. Because the use of active cooling (i.e., a fan) would add unwanted vibrations to the experiments, the boards must be qualified with only passive thermal control.

Thus, the nonconvective environment during a shuttle flight challenged the reliability and survivability of the boards. The components on the boards would obviously operate at higher temperatures, but we did not know how high. This increase in temperature could reduce the reliability to a point where the risk

would outweigh the cost. Startup of commercial boards at reduced temperatures also required verification.

This paper presents a verification method that was first used in the Space Acceleration Measurement System (SAMS) Project to qualify commercial circuit boards for spaceflight. The verification objective is to determine the circuit boards' temperatures when operating in the absence of convection and to ensure that these temperatures are within derated limits. Verification is successful when all the components and final assemblies complete the testing with no failures.

2. BACKGROUND

Because the examples used in this report are specifically related to the work performed on SAMS, a brief background of the project is provided.

At present a number of microgravity and material-processing space experiments are being flown or are being prepared to fly on the space shuttle. Many of these experiments require that the low-gravity accelerations on the shuttle be measured and recorded. Such measurements made prior to SAMS proved to be inadequate for certain microgravity experiments. As a result the Microgravity Sciences and Applications (MS&A) Division at NASA Headquarters requested that the Space Experiments Division at Lewis Research Center in Cleveland, Ohio, develop a suitable acceleration measurement system.

The SAMS project has provided an acceleration measurement system capable of serving a wide variety of space experiments. The system can support experiments in the shuttle middeck, spacelab, and cargo bay. The main components are a remote triaxial sensor head, a microprocessor-driven data acquisition system, and an optical storage device.

The following commercial circuit boards are contained in the SAMS data acquisition system:

- (1) Winsystems, Inc., CPU card #LPM-SBC8-8-SV2
- (2) Winsystems, Inc., memory card #LPM-UMC2-SV
- (3) Technology 80 #900371/Rev. "B" AD card
- (4) K-Systems, Inc., IRIG-B card VTTR-STD-SLO
- (5) ISBX-to-SCSI interface card
- (6) Computer Dynamics processor card CPU-186-SPIO¹

¹Cargo bay design only.

(7) Single Board Solutions SBSxSCSI/CEN PCB L53C80PC-4¹

SAMS used the following test sequence for verification. The reasoning for the sequence and an explanation of each test are given in the next section.

- (1) Engineering unit
 - (a) Component thermal screening
 - (b) Temperature definition
 - (i) Infrared scanning
 - (ii) Thermal vacuum testing
 - (iii) Preliminary thermal operational testing
 - (c) Vibration testing
 - (d) Final assembly testing
 - (i) Thermal screening
 - (ii) Thermal operational testing
 - (iii) Burn-in
- (2) Flight units
 - (a) Component thermal screening
 - (b) Preliminary thermal operational testing
 - (c) Vibration testing
 - (d) Final assembly testing
 - (i) Thermal screening
 - (ii) Thermal operational testing
 - (iii) Burn-in

3. VERIFICATION METHOD

The verification method assumes that the project is taking the approach of building a prototype or engineering unit for qualification testing and then testing the flight units at flight acceptance levels. The engineering unit testing is more extensive than the flight unit testing in that the temperature definition tests (infrared scanning and thermal vacuum testing) are performed. The thermal test temperature ranges are 10 deg C higher and lower for the engineering unit than for the flight unit (ref. 1). The thermal operational tests at acceptance levels are run on the flight units after the parameters have been defined by the qualification testing on the engineering unit.

The test sequence is as important as the tests themselves. The sequence that SAMS settled on took several factors into account. One was to perform the tests as early as possible so that failures could be minimized. Another factor was a desire to test the unit as close to the shipping date as possible to reduce the time between flight testing and flight. The final factor was the need to integrate with other verification testing.

Component Thermal Screening

The test sequence begins with the component thermal screening test. This screening test is performed as soon as possible to minimize failures later in the development of the hardware.

In the SAMS project the screening thermal cycling test consists of cycling the SAMS unit in a nonoperating mode. This test will force flaws in design, workmanship, parts, processes, and materials into observable failures. This test can be run at component level or at full assembly level and is intended

primarily for verifying the workmanship of all parts and assemblies. For the flight unit seven cycles are performed with a temperature range of -24 to 61 °C (a difference of 85 deg C) for inside units and -40 to 70 °C (a difference of 110 deg C) for cargo-bay-mounted units. For the engineering qualification unit seven cycles are also performed, but the temperature range was extended 10 deg C on the high and low ends. A minimum temperature range of -24 to 61 °C is recommended by MIL-STD-1540B (ref. 2). For the SAMS cargo bay design the range was extended because of the calculated expected environment during nonoperating periods found by thermal analysis. Reference 2 calls for a minimum of eight cycles, seven cycles to be performed during component thermal screening and one last cycle to be performed later during final assembly testing. The soak time at the temperature extremes depends upon the response time of the component or experiment assembly. If possible, the ramping time should be 3 deg C/min, or at least the maximum rate to be experienced during the flight (ref. 3).

The thermal screening test is performed because the boards are commercial and may not have been thermally screened by the manufacturer. If thermal screening was performed by the manufacturer, the project may decide not to do this test. Thermal screening has caused weak components to fail. For example, one of the SAMS flight units accidentally had a power spike put into it. Although no obvious failures were detected, two dc-to-dc converters failed during the first three cycles of the screening test. The reason for the failure was traced back to the power spike but was not precipitated out until the thermal testing. The components should be able to perform satisfactorily in a performance acceptance test or checkout before and after the screening test. The screening test is successful if the component passes the checkout after the test.

Temperature Definition Testing

For SAMS engineering unit testing the temperature definition tests (infrared scanning, thermal vacuum testing, and preliminary thermal operational testing) were performed next. The infrared scanning and thermal vacuum testing determine the maximum operating temperatures and verify thermal analysis. They were performed only on the SAMS engineering unit and not on the flight units. The preliminary thermal operational testing was performed on all the units but was only for temperature definition on the engineering unit.

Infrared scanning.—The circuit boards are infrared scanned to find the components with the highest temperature. The board's infrared image enabled the test engineer to quickly determine the hot spots on the board. Figure 1 is an infrared scan of a Winsystems CPU card. Figure 2 is a layout of the card.

The infrared mapping of the board is performed with an infrared camera recording to VHS videotape. For SAMS the cards were inserted into a motherboard that was powered by a 5- and a 12-V power supply. The maximum-temperature positions were recorded in tables and marked on the card layouts as well as on the VHS recording.

A limitation of the process can be seen in figure 3. Notice that the components have warmed the surrounding areas but that

¹Cargo bay design only.

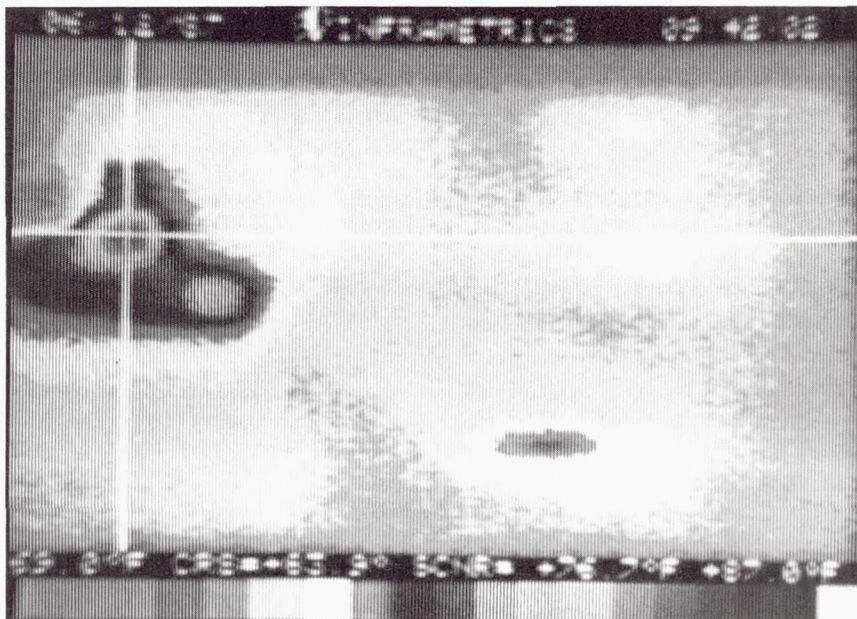


FIGURE 1. - INFRARED SCAN OF WINSYSTEMS CPU CARD.

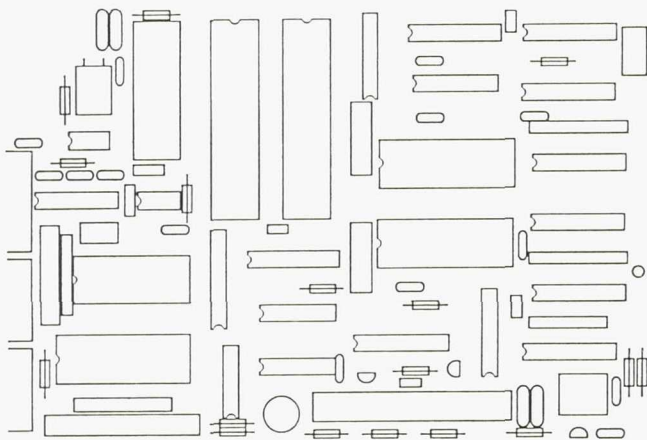


FIGURE 2. - LAYOUT OF CPU CARD.

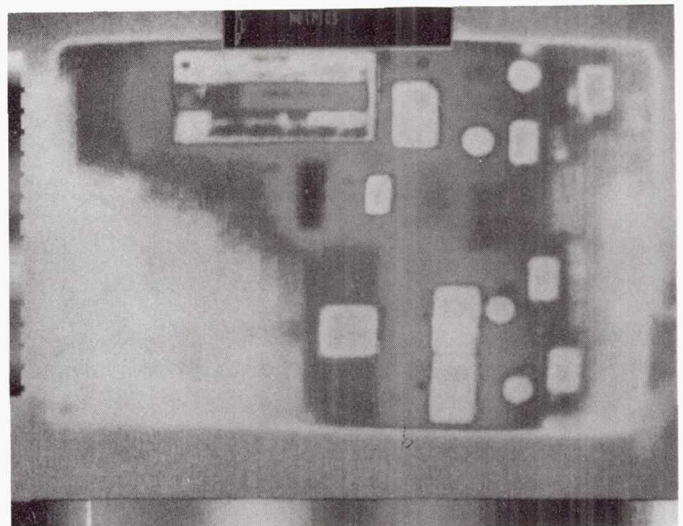


FIGURE 3. - LOW-EMISSION COMPONENTS GIVE INCORRECT TEMPERATURE DATA.

the components themselves appear to be cooler. This apparently contradictory situation is due to the component cases having a lower emissivity than the rest of the board. Emissivity is a parameter that is set on the camera. Thus, if the emissivity of a surface is not known, an accurate temperature cannot be found. Because the emissivity is specified for the whole image, misreadings will occur when a component's or a board area's emissivity varies from the camera emissivity setting that may be correct for other board surfaces.

If acceptable, the whole board should be covered with the same coating so that all the board surfaces will have the same emissivity. The board surfaces shown in figure 3 were later coated with a conformal coating that gave the surfaces approximately a constant emissivity. Because conformal coating has to be applied to all the circuit boards for fire safety and electrical isolation requirements, it does not add extra work to the project.

When this less-reflective coating was applied to the components in figure 3, it was discovered that they were warmer than the surrounding area. Therefore, the components that appear cooler in figure 3 were actually the highest temperature areas. Conformally coating the circuit boards is thus one way to improve the accuracy of the infrared scan. Another way is to probe the board with a thermocouple to verify that the temperature given by the infrared scan is accurate.

The infrared scan does not accurately give the temperatures that the components will experience during a shuttle flight because there is free convection in the room and in the mounting configuration. The circuit boards are installed in a card cage so that the camera can obtain a good picture, but this configuration also enables the boards to dissipate heat with less thermal resistance. During a shuttle flight the board may be in the much warmer environment between two cards.

In the SAMS project the infrared scan was good for revealing certain components that operated hotter than the rest of the board's components. The high-operating-temperature components were identified for further investigation. As part of the investigation, a hot component could be changed with another one that draws less power, such as a complementary metal oxide semiconductor (CMOS) component. When the cards were procured, low-power components were requested and this test verified the degree of compliance. The parts that could not be replaced with a lower power component were at least upgraded to military specification parts if this was not already the case. After all the obvious modifications were made, the testing continued in the thermal vacuum chamber.

Thermal vacuum testing.—The vacuum test is used to simulate the shuttle microgravity orbital environment, where convection is negligible and the only modes of heat transfer are radiation and conduction. In the SAMS project Lexan card guides were used because electrical traces were near the board edge. The Lexan card guides reduced the already poor conduction path off the fiberglass circuit boards. Therefore, radiation heat transfer became the primary heat transfer path off the boards. The boards would operate at lower temperatures if the design included conduction paths through the card guides and through the thermal planes in the boards.

The thermal vacuum test has two objectives. The first objective is to determine the component operating temperatures. The junction temperatures can then be calculated so that they can be compared with the derated component temperatures given in MIL-STD-975H (ref. 4). The second objective is to verify the thermal analysis that is performed on the entire assembly. For SAMS the thermal analysis did not include enough nodes to predict the component temperatures on the boards. Performing a complete thermal analysis on each board layout is costly in time and money and would require test verification anyway. Substituting infrared scanning and thermal vacuum testing for a more complex thermal analysis is more cost effective. The thermal analysis on the experiment assembly is important and was used in SAMS to set test parameters.

The vacuum chamber for the experiment assembly must be able to achieve a vacuum of 10^{-5} torr (ref. 5) and must be able to control the radiant boundary temperature. The vacuum chamber's boundary temperature is controlled with a shroud that encompasses the interior of the chamber. In order to maintain the radiant boundary temperature, the shroud is heated and cooled by flowing heated nitrogen gas and liquid nitrogen through it. This allows the necessary temperature ranges for most of the shuttle boundary conditions given in table 1.

The mounting surface must also be controlled. This was done either passively or actively for the different SAMS configurations. Passively, the mounting structure was connected to the shroud with a conductive path that forced it to a higher temperature; passive control was satisfactory for the middeck, Spacelab middeck experiments rack (SMIDEX), and center aisle units. The higher temperature was within 2 deg C of the predicted mounting surface temperature for a shuttle flight. Actively, a radiator plate was made that was controlled by a

TABLE 1.—SHUTTLE BOUNDARY CONDITIONS
FOR EXPERIMENT ASSEMBLY

Location	Radiant boundary temperature, °C	Mounting boundary temperature, °C	Air temperature, °C
Middeck	32	18 to 49	18 to 27
Spacelab:			
Center aisle	30	32	18 to 27
SMIDEX rack	30	40	18 to 27
Cargo bay:			
Coldplate	-273	2 to 18	(a)
Multipurpose experiment support structure (MPSS) rails	-273	-157 to 104	(a)

^aNot applicable.

refrigeration circulating system and acted as a coldplate simulator; active control was used for the cargo bay unit.

For the SAMS test the cards were mounted in their shuttle flight configuration. Thermocouples were applied to the hottest components that were found by infrared scanning. The circuit boards were conformally coated with 8 to 16 mils of DOW Corning 3140 room-temperature vulcanizing material (RTV). The vacuum chamber boundary conditions were controlled to the shuttle environment conditions. Because of the different SAMS configurations the test was run for an inside unit (middeck, SMIDEX spacelab, center aisle spacelab) and an outside unit (cargo bay mounted on a coldplate). The temperatures of the shroud and the mounting surface varied with the configuration: inside unit, 32 and 40 °C, respectively; outside unit, 40.6 °C² and 2.2 to 18 °C, respectively. Temperature can vary drastically depending on where the experiment is to be mounted: middeck air, 18 to 27 °C; middeck mounting surface, 32 °C; Spacelab, 18 to 27 °C; Spacelab mounting surface, 30 °C; mounting surface (cargo bay, vacuum), -157 to 104 °C; mounting surface (coldplate mounted, vacuum), 2.2 to 18 °C.

The timeframe of the thermal vacuum test is based on reaching temperature equilibrium if applicable. Some experiments may never reach a equilibrium temperature. Because SAMS operates for almost the entire shuttle mission, this was not a conservative approach for it. If the experiment's components do not operate below their derated temperatures at equilibrium, the transient time becomes very important. The components may never get to their equilibrium temperature if they are only powered for a short time. Therefore, the maximum operational time of the experiment should be used.

The thermal vacuum test consists of two primary test runs and for SAMS they were run for each configuration. The first test run was at shuttle environment temperatures in air at standard atmosphere to find out what effect the configuration alone has on the temperature of the components. The air test demonstrates the board's mounting design. During the test the temperatures of hot or sensitive components are monitored. In cases where the component temperature limits are exceeded in

²This is the temperature under the multilayered insulation blanket found by a thermal analysis. An insulation blanket was not available for the test.

this restrained test, a redesign of the mounting configuration is required for the commercial boards to be used reliably. But because this test is performed in air, free convection will help all the boards to perform satisfactorily in most cases. The second test run is performed in a vacuum following the same procedure as the air test.

As expected, the SAMS component temperatures were higher when operated in vacuum than in air. The difference in component temperatures is shown in table 2. The junction temperature calculation is compared with the derated temperature (ref. 4) in table 3. The junction temperature was found by using the following equation:

$$T_{\text{junction}} = T_{\text{case}} + \theta_{jc} P$$

where

T_{junction} component junction temperature, °C
 T_{case} component case temperature, °C
 θ_{jc} thermal resistance, °C/W
 P power, W

The case temperature is the temperature measured in the vacuum test run. The thermal resistance and power values were obtained directly from the manufacturer's specification sheet.

These data were then given to the Lewis Office of Mission and Safety Assurance, where they calculated the reliability of the boards and the entire SAMS system. If the results were unsatisfactory, a redesign was performed to increase the heat transfer off the boards and then the experiment was retested,

starting with the air test. The test results could be unsatisfactory even when the initial configuration of the experiment was designed to enhance heat transfer. If they were, a conductive path would need to be created from the hot component to the main structure, which had a good conduction path to the outside environment.

In order to enhance thermal radiation, most SAMS surfaces were either hard-coat anodized or painted with a black paint. These coatings gave the surfaces tested emissivity values of 0.91 and 0.89, respectively. The thermal vacuum test was then performed at room temperature and the values were assumed to be constant over the thermal testing temperature range.

Preliminary thermal operational testing.—The preliminary thermal operational testing consists of thermally cycling the entire experiment assembly in an operating mode. This test is performed at this time to detect problems early in the hardware development. A more rigorous version of this test is performed later. This test checks the functional capability of the electronic components in a simulated on-orbit temperature environment. A vacuum is not always used to simulate the absence of convection in this test for two reasons. Some experiments cannot be fully functional in a vacuum. An example would be the optical disk drives on SAMS; they will not operate properly in a vacuum. The second reason is the greater time and expense of running a thermal vacuum test as compared with an air test. By raising the air control temperature the component high temperatures can be forced to the same level as seen in the thermal vacuum test. The cold soak temperature

TABLE 2.—COMPARISON OF TEMPERATURES
IN AIR AND VACUUM

Card	Component	Infrared scan temperature, °C	Air temperature, °C	Vacuum, temperature, °C
Winsystems, Inc., CPU card #LPM-SBC8-8-SV2 Technology 80 #900371/ Rev. "B" AD card ISBX to SCSI Single Board Solutions SBSxSCSI/CEN PCB L53C80 PC-4	Input/output chip	28.8	50.9	67.8
	Hybrid Systems, Inc., sample and holds	43.8	59.1	88.7
	Pullup resistors	30.8	59.2	87.6
	Resister network	53.3	60.1	80.3
	4114R-003-221/331	53.3	54.3	85.3

TABLE 3.—DERATED TEMPERATURES OF COMPONENTS

Card	Component	Derated temperature, °C	Component case temperature, °C	Calculated junction temperature, °C
Winsystems, Inc., CPU card #LPM-SBC8-8-SV2 Technology 80 #900371/ Rev. "B" AD card ISBX to SCSI Computer Dynamics processor card CPU-186-SPIO Single Board Solutions SBSxSCSI/CEN PCB L53C80PC-4	Input/output chip	100	67.8	73.2
	Hybrid Systems, Inc., sample and holds	100	88.7	95.9
	Pullup resistors	110	87.6	94.8
	Programmable peripheral interface CMOS; Intel 82C55	100	80.3	95.3
	Resister network	110	47.9	53.3
	4114R-003-221/331	110	85.3	100.3

is the minimum temperature at which the experiment will have to turn on.

The engineering unit is used to define the controlled air temperature needed to have the components reach the same temperature they did in the vacuum test. Data from thermal vacuum testing are used to find target temperatures of components. The components are then forced to these temperatures in air to approximate what they will see on orbit. Once the temperature is found, the qualification temperature is set 10 deg C higher. This chamber setting will also be used for all the subsequent operational tests on the flight units. After the temperature range is defined, 1½ cycles are performed on the engineering unit at qualification levels. The flight units are subjected to the 1½ cycles at acceptance levels that are 10 deg C lower than qualification levels.

The first half cycle is a cold soak with the experiment off. At the end of the cold soak the experiment is powered up to check cold startup. It is then allowed to run during the ramp up to high temperature and during the soak time. The unit is then powered down and powered up again to check warm startup. For SAMS the power supply voltage was varied at the temperature extremes because the shuttle power line can vary from 24 to 32 V. The experiment then operates for another cold half cycle.

The operational test reproduces the temperatures of the thermal vacuum test in the environmental chamber at 1 atm. The differences were all less than 10 deg C for the components that were measured for SAMS. Temperature differences in the vacuum test and the operational test for the Winsystems CPU card and the ISBX-to-SCSI interface card were 5.5 and 9.7 deg C, respectively.

Vibration Testing

The next step in the verification process is random vibration testing. All hardware is subjected to a final random workmanship vibration test to verify that it will survive the lift-off environment. The test level is defined by NASA documents that are specific to mounting location.

Random vibration testing is included as a major part of the verification process because of its dependence on thermal testing. It is important to perform the vibration testing before final assembly thermal testing because most failures "uncovered" by vibration testing are not detected until subsequent temperature cycling (ref. 6).

Final Assembly Testing

Final assembly testing is the final step in assuring that the commercial boards will operate satisfactorily in the spaceflight environment. Final assembly testing repeats some of the earlier testing. The thermal screening and thermal operational tests are performed again with slight changes, and the burn-in test is then performed. This testing attempts to operate the unit in as close to flight conditions as possible. Because of the testing per-

formed early in the development, there is a high probability of success in this test. A performance acceptance test of the unit is performed prior to and after each final assembly test. Successful completion of the acceptance test determines success in the verification testing.

Thermal screening.—The units are subjected to the same thermal screening described earlier, but this time as an entire assembly and only one cycle is performed. The main reason for this test is to bring out most vibration test failures that will only be detectable after thermal cycling.

Thermal operational testing.—The test parameters were defined earlier except for the number of cycles and the number of power ups. The number of cycles is not as well defined because this is an operational test that tries to simulate the flight conditions. On SAMS inside units 5½ cycles were performed for a total of 40 hours operating time. The SAMS units were powered up three times at each low and high temperature and several voltages.

Burn-in.—As the last part of the final assembly test the unit is run for a burn-in period of not less than 100 hours of trouble-free operation. This operational burn-in period should precipitate any additional defects from infant mortality. The operating time in the thermal operational cycling testing should be considered to be part of the 100 hours. For SAMS 40 hours of burn-in was completed during the thermal operational test and another 60 hours at room temperature. Whenever possible, the burn-in should be completely performed during the thermal operational test. This will give the experiment a maximum amount of time operating near the conditions it will have on orbit.

CONCLUSIONS

The verification method uses several different tests to increase the probability of a successful flight. The screening tests that are performed before vibration testing have helped uncover failures early in hardware development. This saves time in the later parts of a program. Infrared scanning of the circuit cards is important in identifying the hot spots on the boards. The accuracy of the infrared scan can be improved by using conformal coating and verified by applying thermocouples to the hot spots shown in the thermal vacuum test. Because most vibration testing failures are not detectable until subsequent thermal cycling, the final assembly testing is important for mission success. The operational and burn-in tests simulate closely 100 hours of operation on the shuttle.

This verification method has been designed to meet reliability requirements. It has proven to be very successful in testing commercial boards and increasing their reliability. SAMS has shipped four units and at present has flown two with no failures of the commercial boards after they had successfully completed this testing.

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