

Investigation of Thermal Test Effectiveness for Spacecraft Electronic Units Using Precipitation Efficiencies of MIL-HDBK-344

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ABSTRACT

Thermal testing of spacecraft electronic units prior to flight provides effective detection of design, process and workmanship defects. Thermal testing subjects units to cold and hot thermal environments beyond those expected in flight. The strength of screening effectiveness depends upon the number of cycles, the temperature range, and the temperature transition rate. MIL-HDBK-344 provides insight into the incurred stresses and quantitative value (precipitation efficiency) of the screening environment using these three test parameters.

In this paper, MIL-HDBK-344 topics applicable to thermal testing of space hardware are summarized and comparisons are made between test environment strengths computed from MIL-HDBK-344 and MIL-STD-1540E. The weighting of these aforementioned test parameters in the precipitation efficiency equation are discussed and assessed. It was found that the fatigue equivalency equations in MIL-STD-1540E specify a significantly larger number of required cycles for various test temperature ranges as compared to cycles computed from MIL-HDBK-344 equations.

INTRODUCTION

Unit-level thermal testing of space hardware has three objectives: (1) environmental stress screening (ESS), (2) performance verification, and (3) demonstration of survival and turn-on capability. Environmental stress screening is the process in which environmental conditions are applied to a test article to force weaknesses or flaws into observable failures so that the

test hardware can be repaired. Performance verification demonstrates that the test article can meet performance requirements in realistic operational environments. This is accomplished through functional tests performed at extreme thermal conditions in environmental tests. Survival and turn-on capability verifies that the test hardware can start, operate, survive and recover from severe, but still realistic flight conditions.

In thermal testing, temperature margins are included in simulated flight conditions to adequately manage mission risk. This is especially true in meeting ESS objectives, where the test environment is more severe than conditions expected in flight. Thermal test parameters, such as the test temperature range and the number of test cycles, are specified to achieve a desired screening effectiveness. The purpose of this paper is to investigate the thermal test screening strength as described in MIL-HDBK-344 [1] and compare its relationships to screening equivalency as specified in MIL-STD-1540E [2].

MIL-HDBK-344 was written to provide techniques and quantitative methods for planning and evaluating ESS programs. Procedures and methodologies outlined in the Handbook were developed under Rome Laboratory contractual and in-house studies [3, 4]. Contractual efforts were also performed by the Hughes Aircraft Company of Fullerton, California and Litton Systems Canada Limited of Toronto, Ontario, Canada. These reports developed test effectiveness relationships apparently based upon electronic part testing for units in primarily terrestrial applications.

IMPORTANCE OF THERMAL TESTING

Unit-level testing of electric boxes consists of three thermal tests: thermal cycling, thermal vacuum and burn-in. Thermal cycle testing subjects the test article to relatively rapid temperature transitions in an ambient pressure environment with extensive functional tests performed at cold and hot temperature plateaus. Thermal vacuum testing is similar to thermal cycle testing, but in a vacuum environment. Temperature transitions in vacuum are commonly not as rapid as observed in the thermal cycle test, but the elimination of convective heat transfer makes the thermal vacuum test a more accurate simulation of thermal conditions expected in flight. Burn-in testing is a continuation of the thermal cycle test, but without functional testing at temperature plateaus. Its purpose is to extend ESS exposure for a consistent duration of all units on the space vehicle.

Ideally, the qualification test should uncover design defects, while the acceptance test finds defects in workmanship, parts, materials, and processes. Performance verification is accomplished through functional tests conducted prior to, during, and after environmental tests. Unit performance must be within specification requirements before the functional test can be deemed successful. With regard to these objectives, the thermal cycle test and the thermal vacuum test have different roles. The thermal cycle test is best suited to accomplish ESS; demonstrating performance, survival and turn-on capabilities is secondary. The reverse is true for thermal vacuum testing. Thermal cycle testing achieves ESS objectives more effectively than thermal vacuum testing because the ambient environment commonly allows for more rapid changes in temperature. The flow of heated or cooled air through the unit enables parts to reach test temperatures relatively quickly, increasing thermal stresses to the hardware.

Unit-level thermal testing of electronic boxes is an extremely important demonstration of hardware quality. The three thermal tests are consistently used on space programs to meet test objectives described in the previous paragraphs. Research performed by the Institute of Environmental Sciences concluded that thermal cycle testing is one of the most effective screens of all environmental tests [5]. The study went on to rank environmental tests for screening effectiveness. The results, shown in Fig. 1, indicate that of the seven highest ranking testing environments, thermal stresses are present in four of them. Thermal cycling had the highest weighted ranking and high temperature test was ranked third.

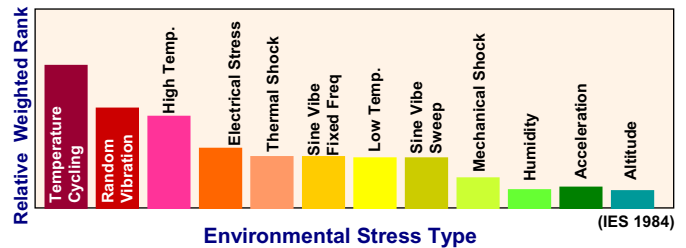


Fig. 1 Ranking of Test Strengths

SCREENING EFFECTIVENESS IN THERMAL TESTING

Gluck [6] addressed the essential thermal test parameters to achieve unit-level thermal test objectives. The number of cycles, test temperature range, temperature rate-of-change, operation of the unit at temperature, and thermal dwell duration were judged the most important parameters. The first two of these have typically been considered the critical parameters in establishing test effectiveness. The temperature rate-of-change has received less study, while a sufficient dwell time and operation of the test article have been viewed as necessary (and not as a variable parameter) for meeting test objectives.

The number of test cycles specifies how many cold and hot functional tests will be performed in the test and the number of temperature transitions between cold and hot conditions. Considerable work was performed in the 1970s and 1980s to assess the proper number of test cycles for meeting ESS objectives [5, 6]. Despite various guidelines recommending a number of test cycles, the appropriate value continues to be debated. Compared to the other thermal test parameters, the number of test cycles has the most direct correspondence to the test duration and hence the cost of the test.

The test temperature range is the difference between the hot and cold temperature plateaus where functional testing is performed. At the unit level of assembly for electronic hardware, the temperature range typically exceeds flight predictions and defaults to a wide range that electronic part manufacturers have stated as appropriate for meeting ESS objectives. As compared to the number of cycles in a thermal test, the test temperature range may be a less controversial topic. However, within the last decade, an ever-increasing number of units, primarily associated with spacecraft payloads, are being developed with restricted performance temperature ranges. Thermal test temperature limits are therefore specified around these limitations, reducing performance margins and ESS effectiveness.

The temperature transition rate is the rate of change as measured on the test article, typically the unit's baseplate, during the transitions between cold and hot

Table 1 MIL-STD-1540E Unit Thermal Test Parameter Requirements

Test Parameter	Qual.	Protoqual	Accept.
Total Number of Cycles	27	27	14
Temperature Range	105°C	95°C	85°C
Temp. Transition Rate	Goal of 3-5°C/min, but not < 1°C/min		
Operation of Unit	Continuously operating except during hot to cold transition		
Dwell Time	Typically 1 hour, but may depend upon unit mass		

test conditions. Unit level transition rates such as 5°C/min have commonly been specified [4, 5], but these values were typically based upon “practical difficulty in achieving high rates of temperature change, especially for massive units as well as because flaw detection [is more difficult] with rapid transitions, was problematic” [6]. In many instances, the transition rate defaults to a best effort value or to thermal chamber capabilities.

Operation of the unit during testing is essential to stress parts and connectors to the points where they may fail. Guidelines throughout industry have consistently required unit operation to meet test objectives. One study reported a doubling of failure rates with unit operation [7]. With an electronics box operating, boards and especially parts will achieve a higher temperature and hence higher stress levels. Thermal spatial gradients will be more severe and temperature differences across connectors, such as solder joints, will be greater. These factors contribute to a higher stress level at the point of unit failure.

Thermal dwell is the time allowed for internal unit locations, such as solder joints and parts, to achieve the test temperature after the unit baseplate has reached the test temperature. When internal locations are stabilized at the test temperature, thermal stresses will be more severe and will aid in meeting ESS objectives. Recommendations for this value have typically been a minimum of one to two hours, but more time may be required for larger mass units. Thermal analyses can be helpful in determining an appropriate dwell time for units of sufficiently large mass.

UNIT THERMAL TESTING FROM MIL-STD-1540E

Military spacecraft for the U.S. Air Force are to be tested to the requirements of MIL-STD-1540. Test parameter requirements specified in this standard are intended to increase the likelihood of mission success for low risk, high priority, national space systems. While the requirements are always tailored to the specific program, considerable thought is given to establishing a test approach that will adequately demonstrate test objectives.

THERMAL TEST PARAMETER REQUIREMENTS - Testing of military spacecraft electronic units per MIL-STD-1540E includes acceptance, protoqualification, and qualification testing. The key thermal test parameters are the same ones previously discussed: number of test cycles, test temperature range, temperature transition rate, unit operation and dwell time. Thermal testing parameters from MIL-STD-1540E are summarized in Table 1.

Protoqualification testing is commonly viewed as a compromise to the qualification test program whereby testing parameters are about halfway between acceptance and qualification levels. Table 1 shows that this is true for the temperature range, but not for the number of test cycles. Protoqualification cycles are identical to qualification cycles and are nearly twice the number required at the acceptance level.

The number of cycles given in Table 1 represents the total number of thermal test cycles to be accrued by an electronics box at the unit level of assembly. This represents the combination of cycles performed in thermal cycle and thermal vacuum testing. If one of these tests is eliminated from the test program, the remaining test must have an increased number of cycles such that the total unit-level cycles accumulated are as given in Table 1.

THERMAL TEST SCREEN EQUIVALENCY - When the required test temperature ranges in Table 1 cannot be demonstrated due to hardware or thermal performance limitations, or when the test temperature range is expanded beyond the required range, MIL-STD-1540E provides equations to determine the equivalent cycles to achieve the desired fatigue exposure. For acceptance, protoqualification, and qualification testing, the respective equations are

$$N_a = 14(85/\Delta T)^{1.4} \tag{1a}$$

$$N_p = 27(95/\Delta T)^{1.4} \tag{1b}$$

$$N_q = 27(105/\Delta T)^{1.4} \tag{1c}$$

In these equations, *N* is the number of required equivalent cycles, the first constant (14 or 27) on the right hand side of the equations is the number of cycles required in MIL-STD-1540E and the second constant (85, 95 or 105) is the required temperature range in MIL-STD-1540E. The test temperature range (ΔT) is the difference between the hottest test temperature (*T*_{max}) and the coldest test temperature (*T*_{min}). The extreme test temperatures *T*_{max} and *T*_{min} are the hottest and coldest temperatures at which functional or performance testing will be conducted. They are not survival or non-operating temperature ranges. This is not to be confused with