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Design of Halt and Environmental Stress Screening Procedures for High Reliability Electronic Products to Reduce Life Cycle Costs

Ali Peiravi

Department of Electrical Engineering School of Engineering Ferdowsi
University of Mashhad Mashhad IRAN
P.O.Box 91775-1111 Postal Code: 9177948974

Abstract: Reliability is one of the main salient assets of modern electronic systems and its improvement is of utmost importance in manufacturingof high-reliability electronic products. The only possible means of improving the operational characteristics of electronic systems and reducing their overall lifecycle costs is improving their reliability. This is possible through designing in reliability at the design and verification stage, and planning a thorough testing program to achieve maximum reliability at minimum costs. Highly accelerated life testing in the initial stages of development and environmental stress screening programs for the later stages of product manufacturing and testing are practical tools in the hands of reliability engineers to achieve this goal. In this paper, the effectiveness of screening programs is analyzed based on which optimum highly accelerated life testing procedures for discovering flaws in design and manufacturing early in the products design and manufacturing are carried out, and environmental stress screening procedures for the testing of manufactured products are planned and implemented for high reliability electronic products. Results of actual HALT and ESS testing are presented.

Key words: Reliability, HALT, environmental stress screening, thermal stress cycles , vibration stress

INTRODUCTION

Reliability is a very important measure of modern electronic products and its growth and improvement are vital to safeguarding progress in manufacturing industries. Reliability at first seems to be just a number without any meaning to many who do not have a deep understanding of its proper application. However, it is the only possible means by which the robustness of modern manufacturing and testing procedures may be measured.

An integrated reliability program includes all reliability testing programs such as Design Validation Testing, Accelerated Life Testing, Highly Accelerated Life testing, Reliability Demonstration Testing, and On-Going Reliability Tests. This should be implemented in such a way that all the reliability needs for the product are covered and there is no extra effort. The design of an optimal reliability testing program will also help reduce the overall life cycle costs of the product while improving the products reliability.

Early in the design stage and in the absence of any physical prototypes, a potential product's reliability may be estimated using existing failure rate databases such as (MIL-HDBK-217F, 1995), 217Plus, SPIDR, PRISM, FIDES, Telcordia SR-332, EPRD, HRD4, CNET, 299B, NSWC, NPRD, etc. Once prototyping is done and a few samples of the new product are produced, one may use life testing procedures to find weaknesses in design, workmanship or parts used.

The product must undergo a reliability growth program before it matures into a high reliability product to be sold in the market. Early life reliability predictions may be used by equipment suppliers to decide wether or not a product meets an especific customer's early life reliability requirement. This was employed by (Chan *et al.,*) who proposed a method for demonstrating early life reliability by combining environmental stress screening strength models and Wald's sequential test for equipment whose early life reliability is described by a Weibull distribution of time to failure. They used screening strength models to transform an

Corresponding Author: Ali Peiravi, Department of Electrical Engineering School of Engineering Ferdowsi University of Mashhad Mashhad IRAN
P.O.Box 91775-1111 Postal Code: 9177948974
Phone: 098-511-881-5100 Fax: 098-511-8763302
E-mil: Ali_peiravi@yahoo.com

environmental stress test (e.g. temperature cycling/random vibration) to an equivalent constant heat test to obtain an equivalent number of field operating hours which could be used to compute the accept and reject boundaries of Wald's sequential test plan when combined with the Weibull model of early-life reliability. (Kai *et al.,* 1998) attempted to improve product reliability by using a combination of orthogonal array experiments with environmental stress testing since reliability of a product is related to its performance degradation. Optimal levels of design parameters were suggested so that the product performance will be less sensitive to environmental stresses and thus more reliable.

Microelectromechanical systems (MEMS) are being considered more and more for use in military applications and products ranging from aircraft and communications to munitions may employ MEMS in the near future. Already the use of tiny copper structures in nanoelectronics has been suggested for MEMS fuzes for military munitions. However, MEMS reliability implies that MEMS devices must perform their required functions for the duration of their mission under a predefined environmental profile. Packaging and interconnect reliability are also of utmost concern in MEMS reliability. Understanding the major failure modes of any product is vital in development of reliability tests to detect the potential for failures. Only then can long-term reliable performance be assured. MEMS devices that are to operate in harsh military applications may suffer from such failure modes as wear and stiction. Corrosion may also become a major failure mechanism in military application of MEMS devices which may use metallics to enhance robustness. (Mason *et al.,* 2006) presented MEMS reliability test guidelines implemented to ensure adequate long-term performance of MEMS devices in fielded and emerging military systems. In some instances, the lack of failure rate data makes it difficult to perform reliability predictions. An example of this is micro-electro-mechanical systems (MEMS) which are being developed fast with recent advances in nanoelectronics and micromachining. (Zurino, *et al.,* 2008) addressed this issue as a barrier to the utilization of MEMS in military applications especially the impacts of long-term storage and environmental exposure on the reliability of MEMS devices. They performed some tests on prototype mechanical Safety and Arming devices for weapons with the aim of developing standardized test protocols, formulating reliability models, establishing design criteria and identifying critical parameters in support of the development effort. They peroformed Environmental Stress Screening (ESS) tests on samples of the device and developed a failure modes and effects analysis for modeling reliability.

One possible approach to reliability improvement is integration of parts into more modern components with a higher reliability. Integration of discrete parts using modern VLSI gates such as FPAAs and FPGAs are presented as a means of improving system reliability by (Peiravi, 2008) The improvement in reliability can also be achieved by other means such as derating of parts as shown by (Peiravi, 2009), use of redundancy in design or proper design of accelerated life testing and environmental stress testing. To ensure that products entering the market have a high reliability, proper environmental stress screening programs must be designed and implemented. However, testing for reliability id usually expensive and an attempt should be made to minimize testing costs while assuring relaibility. (Gatelani *et al.,* 2007) attempted to optimize testing time by a process of screening with random vibration. Their proposed environmental stress screening procedure is based on the components and the layout of the board. Another approach reduce the overall costs is the use of commercial off-the-shelf products in developing the reliability tests. An example of this is presented by (Gutterman, 2007) in the development of the test system for the Joint Strike Fighter which is the future fighter aircraft for the U.S. armed forces. (Gutterman, 2007) argued many new airborne products will have to be tested and maintained for the next few decades due to the JSF program. He stressed that the Joint Strike Fighter F-35 Lightning II is not any different from other sytemsa and can use Alternate Mission Equipment (AME) that refers to military equipment that can be installed on, or removed from an aircraft to achieve specific mission requirements. He concluded that the AME tester program using COTS products and off-the-shelf testers can be used for Joint Strike Fighter testing in order to reduce the development and life cycle costs. The tester selected for for manufacturing, ESS and depot-level testing was the Lockheed Martin LM-STAR test set which is an open-architecture test set with most of the test set's components being Commercial Off The Shelf (COTS) products. The present research stresses the optimal design of the types of tests and the way to perform them in order to minimize overall testing costs while achieving maximum reliability growth in the design and development phase, and maximum reliability through ESS testing.

ESS Effectiveness:

There are many different test usually performed during reliability growth and environmental testing since many factors such as temperature, vibration, humidity, corrosion, mechanical shock, thermal shock, etc. may affect a product's performance. Environmental stress screening programs are sometimes planned by copying down the instructions in a handbook in a cookbook fashion without a deep understanding of their effectiveness. It is not just important that ESS is being carried out. Rather, it is how effective these tests are in precipitating potential failures in the product that matters. Since costs incur inperforming the tests, the question as to which of these tests are more effective, and how they should be implemented to yield an optimum strategy is of great economic concern. (Vellmure *et al.,* 1990) proposed improvements in ESS program at Litton Guidance & Control Systems by adopting a philosophy that included sequential performance of thermal cycling and random vibration, with a general rule of following random vibration with thermal cycling. They obtained an improvement of acceptance test first-pass yields during factory system testing and a 30% yield improvement from a beginning yield of 50% in 1984 to a first-pass acceptance test yield of 80% during the highest production period of the program. They also achieved a significant reduction in the number of systems returned under warranty in spite of a steady increase in production rates. In light of this fact, one may design an optimum testing program by considering the effectiveness of the various tests being performed. Many ESS programs suffer form lack the methodology for assessing the effectiveness of the tesing process and do not provide a basis for optimizing the ESS screens. Fortunately, the methodologies and procedures to quantify the ESS process, assess its effectiveness and provide feedback to allow changes to the screens may be found in (DOD-HDBK-344). (Schmidt *et al.,* 1992) proposed an ESS program for on an electronic countermeasures (ECM) pod system using the procedures of (DOD-HDBK-344) whereby a prediction of of the number of latent defects in the system was made before any screening was applied. They proposed to periodically monitor the ESS tests at the subassembly and systems levels using control charts based on the estimate of latent defects and the test strengths. They suggested corrective actions in the form of reducing latent defects and/or modifying the screens when the control limits were exceeded to allow an assessment of the ESS effectiveness and to provide a means for keeping the process under control.

Thermal Screening Methods:

One common thermal testing method is the soak test where the product is usually operated in its actual operating environemt for a total of 96 hours. Although this is a simple test, it provides us with no reliability information. A more sophisticated reliability testing procedure especially for electronic equipment is called burn-in where the product is placed under constant temperature for a certain period of testing time. Yet a more comprehensive test is thermal cycling where the product undergoes several cycles of temperature variations in which a product is heated to a high temperature, maintained at that temperature for a while, then cooled down to a low temperature, maintained at that temperature for a while, and then the whole cycle is repeated over and over again. The upper and lower dwell temperatures, the rate of change of temperature, and the number of test cycles msut be designed in advance. Accelerated thermal stress to determine a product's lifetime, or discover its modes of failure is another possible relaibilty test.

Screening Efficiency:

The screening efficiency of a given environmental screening test is the probability that the test will cause the precipitation of latent defects in the product into detectable failures. For example, if we specify a screening efficiency of 90 percent, then we can expect to precipitate 90% of failures that would otherwise have occurred during the early life of the product if we use an appropriate environmental screen. Various models for screening efficiency have been reported in the literature.One may cite the Hughes and the RADC models as the most widely accepted models. The Hughes model of screening efficiency for constant temperature burn-in is given in (1):

$$SS = 0.85(1 - \exp\{-0.0023[\ln(e+1)]^{2.7} T^{0.5} R_D{}^{0.6}\}) \tag{1}$$

where T is the burn in test time in hours, and R_D is the difference between the burn in test and the ambient temperature. The values of screening efficiency for several testing temperatures is shown in Figure 1.

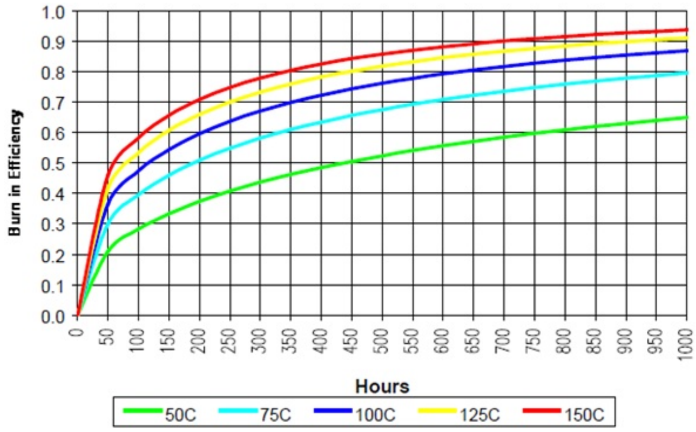

Fig. 1: The screening efficiency of constant temperature burn-in based on the Hughes model as reported in the literature

The screening efficiency for burn in at constant temperature may be computed from (2) as proposed by RADC:

$$SS = 1 - \exp\{-0.0017(T_R + 0.6)^{0.6} T_b\} \tag{2}$$

where SS indicates burning efficieny, T_R indicated the difference between the testing temperature and ambient temperature, and T_b indicates the total burn in time. This is shown in Figure 2 for burn in at constant temperatures of 50, 60, 70, 80, 90 and 100 degrees Celcius. The results indicate that a lot of time must be spent to get an acceptable result which means that extensive manpower and testing resources must be allocated for this purpose. The results shown in Figure 2 also indicate that the higher the testing temperature is, the less time is needed to achieve the same testing efficiency.

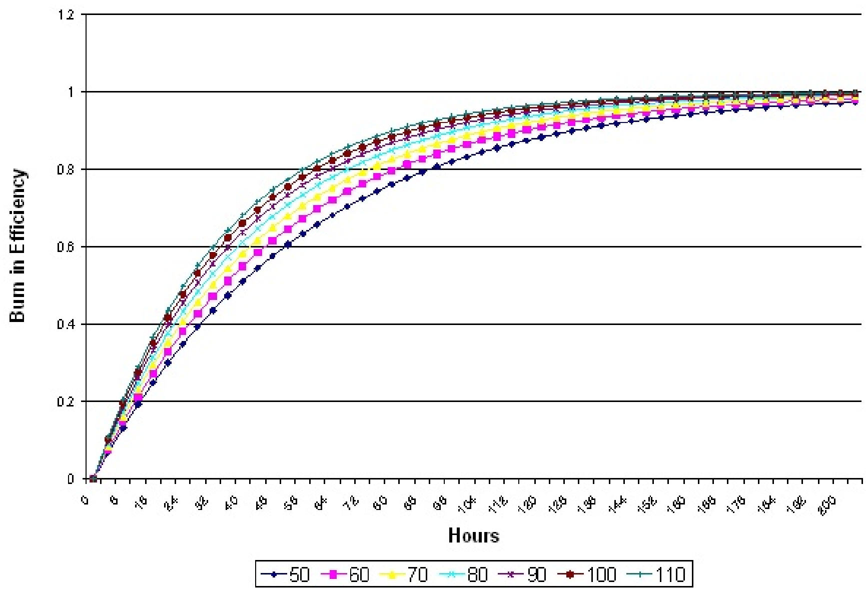

Fig. 2: The testing efficincy of burn in at constant temperature versus testing time

The number of hours needed for performing burn in at a constant temperature for an efficiency of 0.999 are shown in Table 1.

Table 1: The number of hours needed for constant temperature burn-in efficiency of 0.999

Temperature difference between the burn-in chamber and the ambient temperature in degrees Celcius	Testing time required for a testing efficiency of 0.999
50	388
60	348
70	312
80	292
90	276
100	256

The other alternative for thermal testing is thermal cycling. This procedure requires a more sophisticated chamber. However, better results may be obtained. The screening efficiency of the thermal cycling may be computed from (3) as proposed by RADC:

$$SS = 1 - \exp\{-0.0017(T_R + 0.6)^{0.6}(\ln(e + \Delta T))^3 N_{CY}\} \tag{3}$$

where SS shows screening efficiency, T_R indicates the temperature span being the difference between the high and low extremes of the cycle, ΔT indicates the rate of change of temperature in the cycle, e is 2.781, and N_{CY} indicates the number of thermal cycles performed in the test. The testing efficincy of thermal cycle screening for a temperature span of 60, 80, 100, 120, 140, 160, and 180 degrees Celcius for various rates of change of temperature from 2.5 degrees Celcius per minute to 50 degrees Celcius per minute are shown in Figures 3, 4, 5, 6, 7, 8 and 9 respectively.

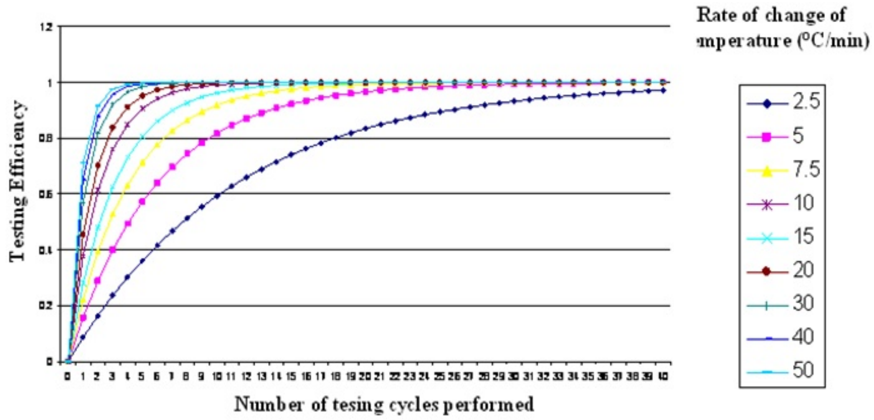

Fig. 3: The testing efficincy of thermal cycle screening for a temperature span of 60 degrees Celcius

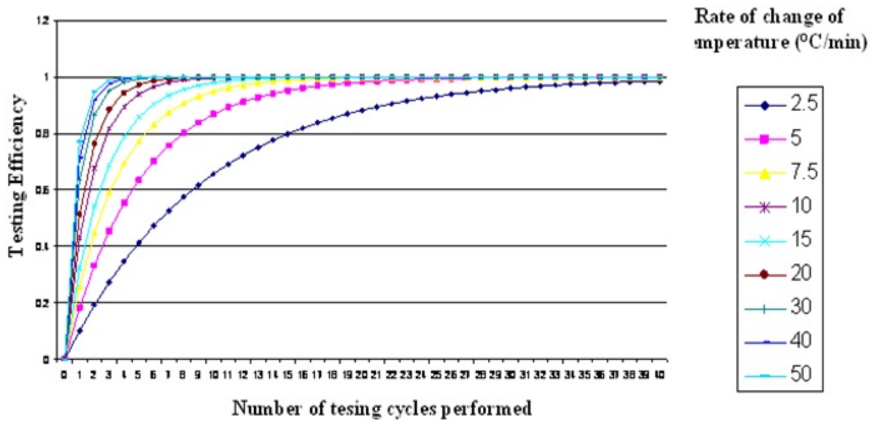

Fig. 4: The testing efficincy of thermal cycle screening for a temperature span of 80 degrees Celcius

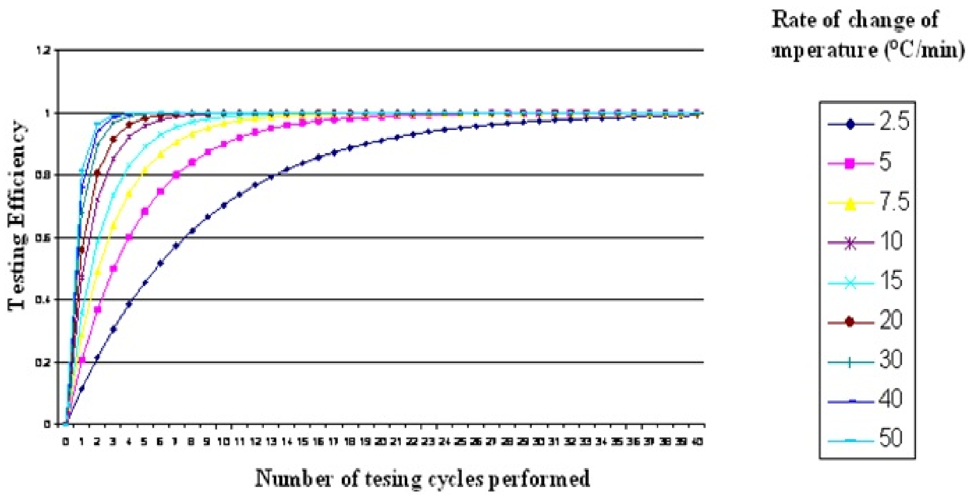

Fig. 5: The testing efficincy of thermal cycle screening for a temperature span of 100 degrees Celcius

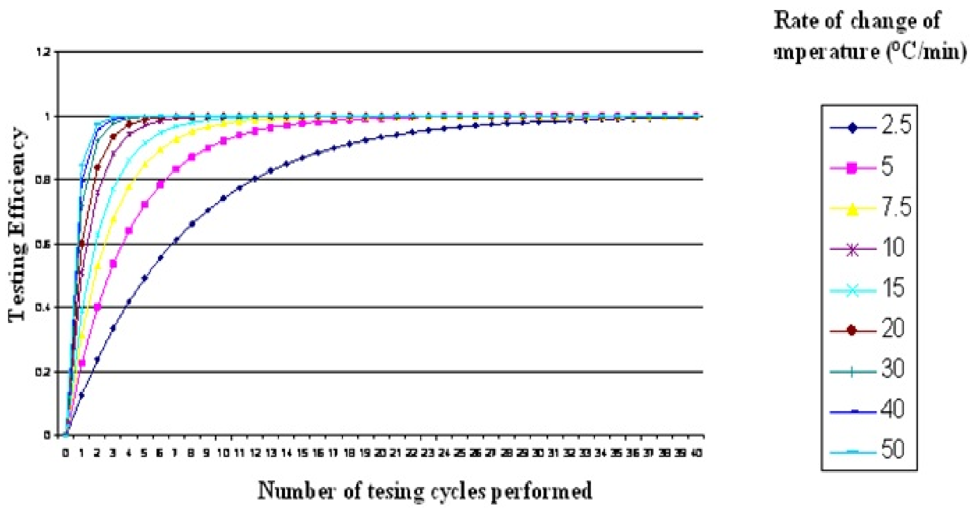

Fig. 6: The testing efficincy of thermal cycle screening for a temperature span of 120 degrees Celcius

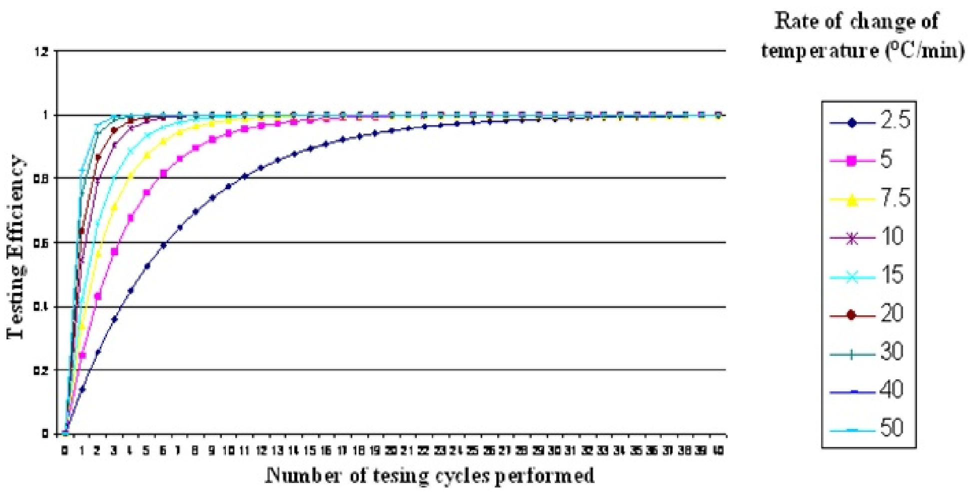

Fig. 7: The testing efficincy of thermal cycle screening for a temperature span of 140 degrees Celcius

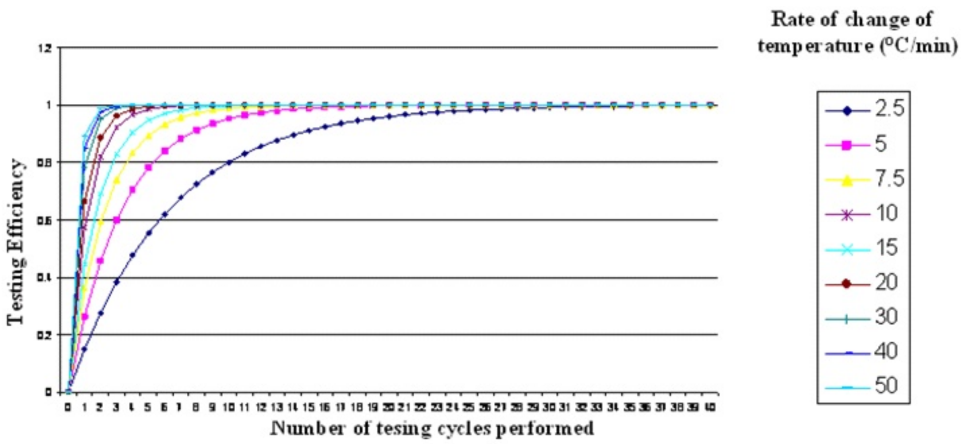

Fig. 8: The testing efficincy of thermal cycle screening for a temperature span of 160 degrees Celcius

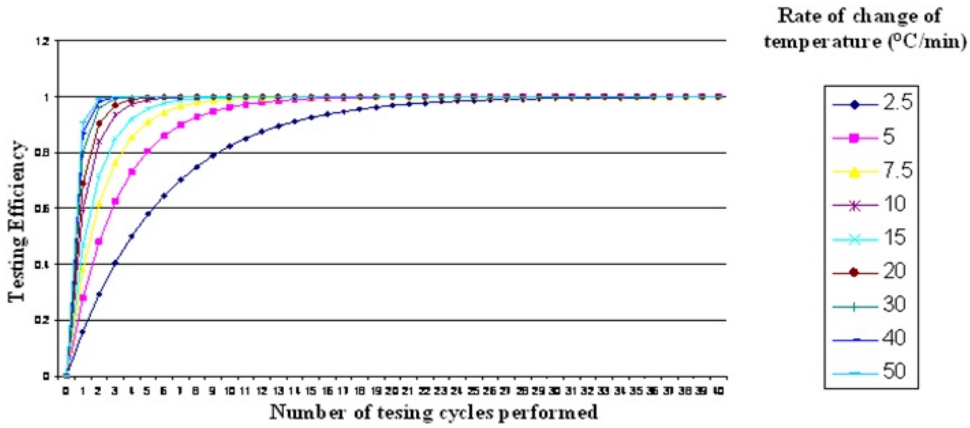

Fig. 9: The testing efficincy of thermal cycle screening for a temperature span of 180 degrees Celcius

The data portrayed in Figures 3, 4, 5, 6, 7, 8 and 9 may be utilized for an optimal ESS thermal cycling screen for any required amount of screening efficiency. For example, the results for a testing efficiency of 0.999 are summarized in Table 2 which indicated the required number of thermal stress cycles versus different rates of change of temperature.

Table 2: The required number of thermal stress cycles versus different rates of change of temperature for a testing efficiency of 0.999

Temperature Span	2.5°C/min	5°C/min	7.5°C/min	10°C/min	15°C/mi	20°C/min	30°C/min	40°C/min	50°C/min
60	77	42	28	22	15	12	9	7	6
80	65	35	24	18	13	10	7	6	5
100	57	30	21	16	11	9	7	5	5
120	51	27	19	14	10	8	6	5	4
140	47	25	17	13	9	7	5	4	4
160	43	23	16	12	9	7	5	4	4
180	40	22	15	11	8	6	5	4	3

Figure 10 shows the number of required thermal cycles versus the testing temperature span for different rates of temperature in the test chamber for a testing efficiency of 0.999. As can be seen from this Figure, a fewer number of thermal cycles is needed when testing with a greater temperature span and at higher rates of temperature change. Of course, both of this measures require more sophisticated testing facilities.

The results shown in Figure 10 indicate that fewer thermal cycles are required in order to achieve the same results if we test using a higher temperature span and impose higher rates of change of temperature. For example, performing a thermal stress cycle test on a product with a temperature rate of change of 50 degrees Celcius per minute can expose the products flaws in three to six short thermal cycles, while performing a similar test with a rate of change of only 2.5 degrees Celcius per minute would take 43 to 77 long test cycles to expose the product's flaws.

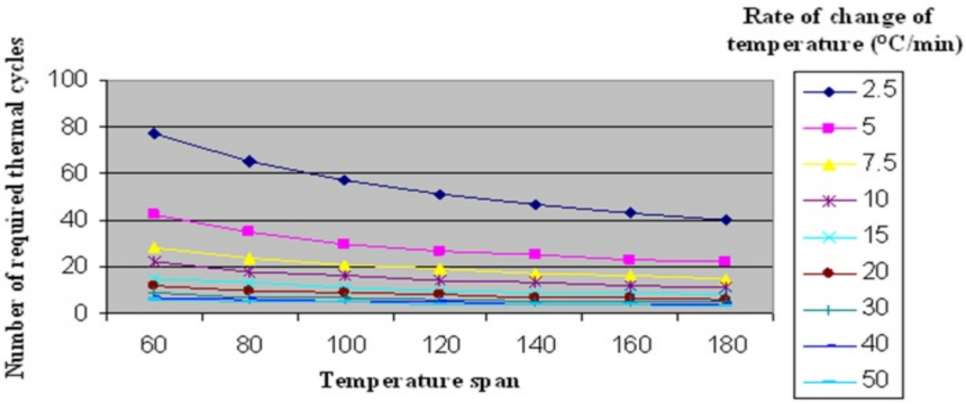

Fig. 10: The number of thermal cycles required to achiece a test efficiency of 0.999

A comparison of the results for burn in at constant temperature and thermalcycling shows that burn in at a temperature of 100 degrees Celcius would require 256 Hours of testing for a testing efficiency of 0.999 to expose a product's flaws. The same product tested at a temperature rate of 50 degrees Celcius per minute. may be tested for only a few minutes to expose the product's flaws.

One should also remember that the time to carry out each cycle of the thermal testing at a lower rate of temperature change would also require a lot more time to perform. This would require more manpower and longer use of the testing equipment to perform the testing and would thus greatly increase the cost of testing. The total time required for testing assuming only a five minute stay at either temperature extreme to perform the functional testing of the product under test is shown in Table 3 for a testing efficiency of 0.999 and Table 4 for a testing efficiency of 0.9999.

Table 3: Therequired ESS testing time assuming a five minute stay at the upper and lower temperature limits for a 180 degree temperature span and a testing efficiency of 0.9990

The rate of change of temperature in degrees Celcius per minute	The number of thermal cycles required	Time required to go through the temperature extremes in each cycle in minutes	Time required for temperature stabilization in each cycle in minutes	Time required to cycle through the test once in minutes	Total time required for thermal stress cycling inminutes
2.5	40	144	15	174	6960
5	22	72	12.5	97	2134
7.5	15	48	10	68	1020
10	11	36	7.5	51	561
15	8	24	5	34	272
20	6	18	4	26	156
30	5	12	3	18	90
40	4	9	2	13	52
50	3	7.2	1	9.2	27.6

Table 4: Therequired ESS testing time assuming a five minute stay at the upper and lower temperature limits for a 180 degree temperature span and a testing efficiency of 0.9999

The rate of change of temperature in degrees Celcius per minute	The number of thermal cycles required	Time required to go through the temperature extremes in each cycle in minutes	Time required for temperature stabilization in each cycle in minutes	Time required to cycle through the test once in minutes	Total time required for thermal stress cycling inminutes
2.5	76	144	15	174	13224
5	40	72	12.5	97	3880
7.5	28	48	10	68	1904
10	22	36	7.5	51	1122
15	15	24	5	34	510
20	12	18	4	26	312
30	9	12	3	18	162
40	7	9	2	13	91
50	6	7.2	1	9.2	55.2

The results show that while 108.5 hours of continuous testing are required for performing only one screening operation at a temperature rate of change of 2.5 degrees Celcius per minute for a testing efficiency of 0.999, the same results may be achieved in only 27.6 minutes using a rate of change of temperature of 50 degrees Celcius per minute. Moreover, to achieve a testing efficiency of 0.9999, one should spend 206.6 hours of continuous testing for performing only one screening operation at a temperature rate of change of 2.5 degrees Celcius per minute, while the same results may be achieved in only 55.2 minutes using a rate of change of temperature of 50 degrees Celcius per minute.

Destructive Testing:

In order to determine the weaknesses of the product, accelerated destructive life testing must first be performed. The extreme limits of the parameters which the product can sustain should be discovered. This may be found by either a thorough analysis of the datasheets of the parts making up the product, or by performing an accelerated destructive type of thermal cycle such as shown in Figure 11.

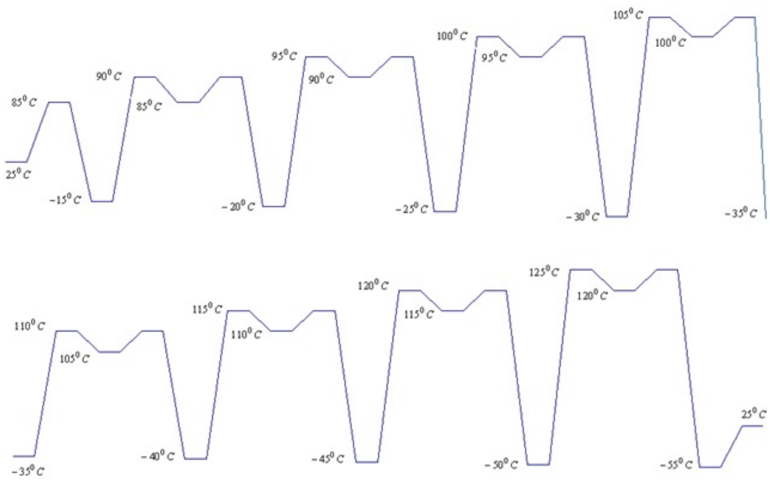

Fig. 11: The proposed destructive thermal cycle – theproduct is exposed to the test until it fails.

The aim of this test is to run the product up to the point where it fails. Then the root cause of the failure is analyzed and eleiminated by changes in design, or manufacturing process. Then the test is performed again, until all such failures are discovered and totally eliminated from the product. A good test design is very important since it can help increase the product's manufacturing yield and substantially reduce warranty costs. In a proper design, the product being tested must closely follow the desired variation as shown in Figure 12.

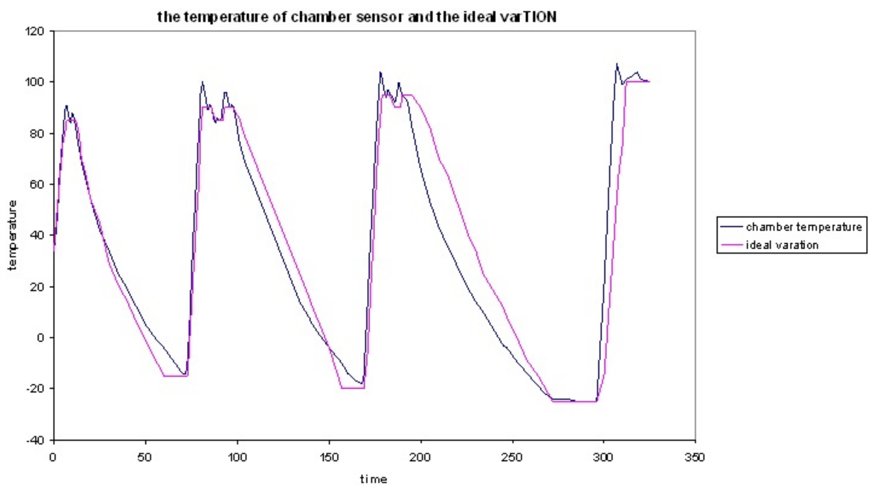

Fig. 12: The temperature profile of the chamber compared with the expected temperature variations indicating proper design of HALT

Of course, the individual boards in the system do not exactly all follow the same temperature profile. An example of actual results of testing until failure are shown in Figure13 which shows the temperature profile of on of the boards in the product under test. Of course, upon each failure the root cause of the failure should be analyzed and corrective measures should be put in effect.

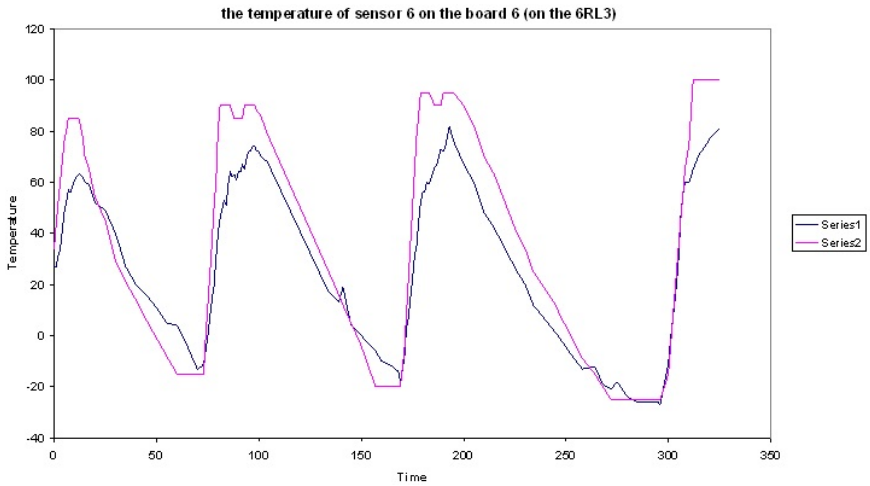

Fig. 13: The temperature profile of one of the boards of the electronic product under test compared with the expected temperature variations during HALT

ESS Design:

After the above accelerated life tests have been completed and the product attains maximum reliability growth, one may design a product environmental stress screen. In such a design many parameters should be carefully considered such as the size of the chamber, the rate of airflow through the cahmber, the place to put the sensors, the rate of change of temperature during the test, the high and low temperatures, the dwell time at each temperature extreme, etc. as shown in Figure 14.

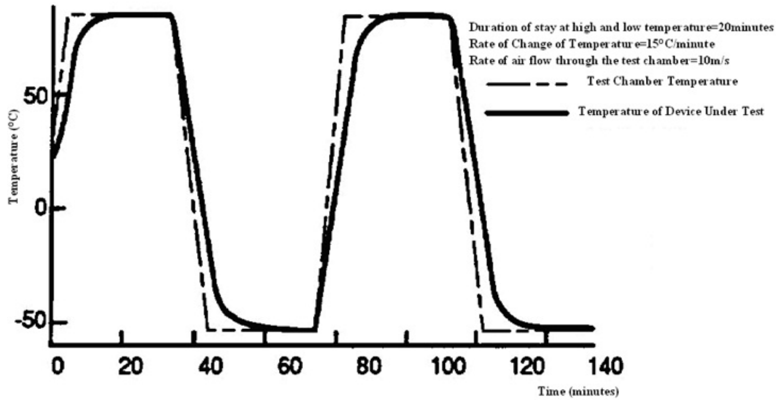

Fig. 14: A typical thermal cycling screen indicating the various parameters of interest

If in the design of a thermal cycle screen the airflow is not enough for the temperature of the part under test to reach the temperature of the chamber, or the rate of change of temperature is too fast for the system to follow it, the test will not be properly done since the device under test cannot follow the chamber temperature as shown in Figure 15.

Given the information presented in Figures 3,4,5,6,7,8 and 9, an ESS thermal cycle design for any screening efficiency may be designed. The data shown in Tables 3 or 4 may be used for an optimal ESS design if an screening efficiency of 0.999 or 0.9999 is desired.Similar designs are possible for less stringest screening efficiency reuirements. Two examples thermal cycling screen performed in this study are shown in Figures 16 and 17 which indicate that the above problem exists but has been dealt with properly in our research. The low to high rate of change of temperature in Figure 16 is 50 degrees Celcius per minute in the test experiment shown in Figure 16, while it is 25 degrees Celcius per minute in the test experiment shown in Figure 17. Likewise, the high to low rates are chosen to be 10 and 5 degrees Celcius per minute, respectively.

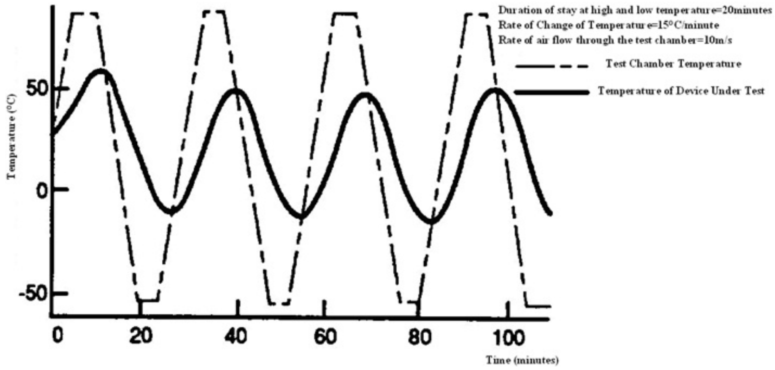

Fig. 15: A typical poorly designed thermal cycling screen indicating the inability of the device under test to follow the desired temperature

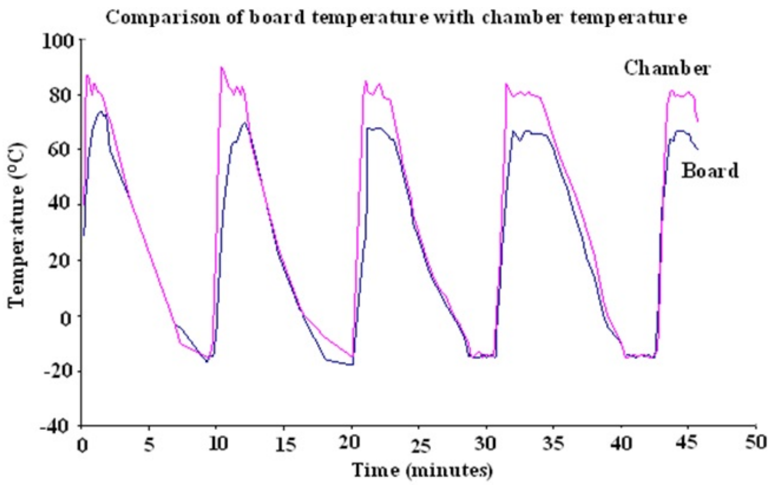

Fig. 16: An ESS thermal cycling screen using low to high rate of 50 degrees Celcius per minute and a high to low rate of 10 degrees Celcius per minute.

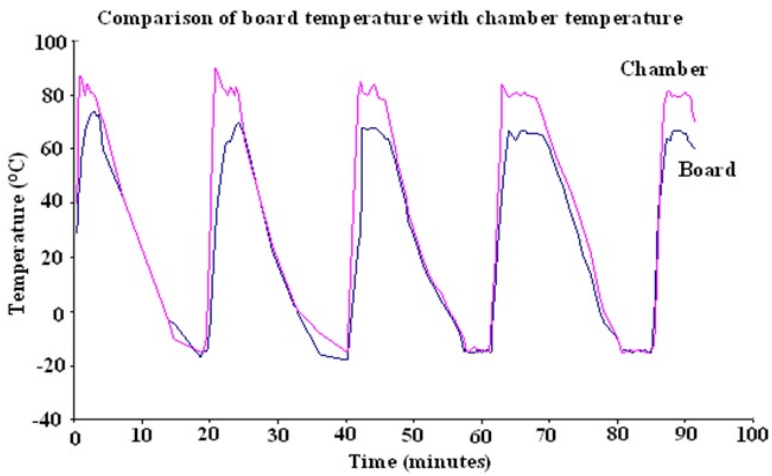

Fig. 17: An ESS thermal cycling screen using low to high rate of 25 degrees Celcius per minute and a high to low rate of 5 degrees Celcius per minute.

The HALT tests were all performed through modifications of an existing thermal chamber since it did not meet the requirements of the proposed program. The same modified chamber was later used for the thermal cycling ESS program.

Vibration Screening Efficiency:

One may also design an optimal vibration screening program by considering the screening efficiecy of the various possible vibration tests. The screening efficiency for fixed frequency sine wave tests are given by (4)

$$SS = 1 - \exp\{-0.00047G^{0.49}T_{FFS}\} \tag{4}$$

where G is the fixed vibration level, and T_{FFS} is the time of the fixed frequency vibration test of the product in minutes.

The screening efficiency for sine sweep vibration screening test is given by (5)

$$SS = 1 - \exp\{-0.000727G^{0.863}T_{SS}\} \tag{5}$$

where G is the sine sweep vibration level, and T_{SS} is the time of the sine sweep vibration test of the product in minutes The screening efficiency for random vibration tests are given by (6)

$$SS = 1 - \exp\{-0.0046G^{1.71}T_{RV}\} \tag{6}$$

where G is the vibration level in g's and TRV is the time of the random vibration test of the product in minutes.

Of course, the RADC models are not meant to be the final word. They rely on certain data for the parameters of the model. The temperature cycling models were derived from the temperature cycling curves of (NAVMAT P-9492, 1982) which relate the failure rate of electronic equipment to the number of temperature cycles. The burn in at constant temperature model was derived by adapting the temperature cycling model for a fixed value of temperature gradient and zero cycles. The vibration models have been obtained using raw data supplied by the Grumman Aerospace Corporation in Grumman report ADR 14-04-73.2 by (Kube *et al.,* 1973). There are cases where one may get a better model as reported by (Kececioglu, *et al.,* 2002) where they present an example and show that the optimum screening strength equations derived using the least squares method where historical data are available may be slightly different from the RADC model. For example, they indicate that the screening efficiency of the thermal cycle screen for the case they reported is given by (7):

$$SS = 1 - \exp\{-0.00197(T_R + 0.6)^{0.8521}(\ln(e + \Delta T))^{1.7467}N_{CY}^{\ 0.8335}\} \tag{7}$$

They have presented similar results for other screens. For example, their fitted model to data for random vibrationscreen is compared with the RADC model is Figure 18.

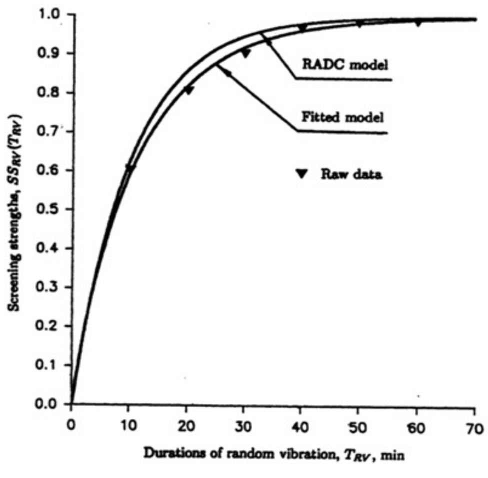

Fig. 18: A comparison of RADC model and fitted data for random vibration screen strength presented by (Kececioglu, *et al.,* 2002).

The vibration screening tests in this study were planned in a similar fashion to the thermal tests using the RADC screening efficiency and were performed using LNG Model B335 with the characteristics shown in Table 5.

Table 5: The general characteristics of the vibration platform

Item1	Characteristics	Rating
1	Force rating	8000 lb(80KN)
2	Useful frequency rage	5Hz to 3000 Hz
3	Maximum Acceleration	150 g vector
4	Rated velocity	70 in/s (1778 mm/s)
5	Rated displacement	1 in (25.4 mm) peak-tp- peak
6	Fundamental resonant frequency	2350 Hz(nominal)
7	Rated static load(vertical)	2000 lb(8.9 kn)
8	Rated lateral load	1000 lb (4.4 kn)
9	Flexure stiffness	530 lb (2.4 kn) per inch
10	Effective overtravel limits	0.625 in(15.9 mm)
11	Body suspention(vertical natural frequency)	<2 Hz
12	Body suspention(horizental natural frequency)	< 1 Hz
13	Maximum load 10 g vector	1700 lb(7.56 kn)

Conclusions:

The optimal design of environmental stress screening procedures for high reliability electronic products is vital in assuring the products reliability while imposing minimum costs. A proper design requires a thorough understanding of reliability, testing procedures, HALT, ESS as well as thermodynamics. The desirable level of screening efficiency should be chosen and the ESS program should be designed after the product has undergone its full reliability growth program using HALT. The use of the existing models to predict screening efficiency helps reduce overall costs while assuring the precipitation of latent faults in the product which may show up in the field if not uncovered through ESS testing. The units under test failed often during the program, and many revisions in the product were implemented before satisfactory results were obtained.

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