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Environmental Stress Screening 2000

Final Report

April 30, 1997

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Authors and Sponsoring Organizations

The following identifies the authors of this report and the organizations that sponsored the effort conducted under the National Center for Manufacturing Sciences (NCMS) Environmental Stress Screening (ESS) 2000 Project.

Authors

The individuals presented below formed the Project Steering Committee and authored this project final report.

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Charles Felkins, Storage Technology Corporation, is an Advisory Test Engineer in the Advanced Manufacturing Department. He has 25 years of test engineering experience in test equipment design/development, management, and manufacturing test processes. For the past 10 years he has been utilizing Highly Accelerated Life Test (HALT) and Highly Accelerated Stress Screen (HASS) processes to test all of StorageTek's product lines; that is, tape drives, power supplies, electronic equipment racks, card sets, printed circuit boards, displays, motors, cameras and robotics.

Mark Gibbel graduated from California State Polytechnic University Pomona campus with a BS in Mechanical Engineering. He has been involved in design and test of advanced electronic packaging since 1977, when he developed the thermal models for Hewlett Packard's flip-chip technology. He has dedicated his professional career to failure physics-based test and verification methodology development and implementation, with a particular interest in space flight electronics. He has been a member of the Reliability Technology Group within the Reliability Engineering Section of the Jet Propulsion Laboratory since 1985. He has innovated and managed many research projects within NASA's Test Effectiveness Program. He is actively involved in the IEEE, is Vice Chair of IEEE's Components Packaging and Manufacturing Technology (CPMT) Technical Committee Seven (TC-7) Environmental Stress & Reliability Testing, Southern California Region. He is a past Executive Committee member of the San Diego Chapter of IEEE's Components, Hybrids and Manufacturing Technology (CHMT) and the Executive Committee of the Los Angeles Chapter of IEEE's Reliability Society. He has published many papers on the subject of failure physics based test testing for electronic hardware, He has taught several courses in the field of thermal reliability, thermal design, analyses and testing of electronics.

John Hess, Storage Technology Corporation, is a research and development engineer in the Advanced Technology department. He received his BS and MS in Mechanical Engineering from Texas A&M University.

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Andrew Quintero is a member of the Technical Staff in the Aerospace Corporation's Environmental Criteria and Test Department. He received his BS in Electronic Engineering Technology from California Polytechnic State University in San Luis Obispo in 1988. Before joining the Aerospace Corporation in February 1993, he worked at Hughes Aircraft Company in the Space and Communications Group as a Reliability Engineer for five years. Presently, he is one of the primary developers of an engineering database intended to be a national repository of space hardware pedigree data.

Ron Silver is a member of the Technical Staff of Bell Laboratories at Lucent Technologies Engineering Research Center in Princeton, New Jersey, and is part of their Environmental Stress Test engineering group. He received a BS and MS in Electrical Engineering from the University of Pennsylvania in 1960 and 1965, respectively, and a Ph.D. in Biomedical Engineering from Drexel University in 1981. Before joining Bell laboratories in 1981, he worked at Philco Corporation's Government and Industrial Logic Design Division starting in 1960, and joined the General Electric Re-Entry Systems Division in 1965 in the RF Communications Design Department.

Sponsoring Organizations

All work for this project was performed at the participants' facilities using their existing capital equipment supplemented by program-specific capital equipment. Each participating company has significant investment in environmental stress screening equipment and people.

The Aerospace Corporation: The Aerospace Corporation provides architect-engineering services for military space and launch systems, and for other projects related to national security. The Aerospace Corporation has a number of laboratories and technical support facilities. A component failure analysis lab performs detailed piece part failure analysis on integrated circuits to determine failure mechanisms. A team of fatigue experts performs solder fatigue analysis as well as develops fatigue models for predicting fatigue life. Modeling and risk assessment expertise is also employed. Many of the technical staff have their doctorates and extensive experience in their fields of expertise.

Jet Propulsion Laboratory: JPL is an operating division of the California Institute of Technology and performs research, development, and related activities for the National Aeronautics and Space Administration (NASA). JPL is an internationally known institute with a work force of 6,400 people. The laboratory's work requires the highest reliable products for space and planetary missions.

Lucent Technologies: Bell Laboratories at Lucent Technologies (formerly AT&T) have complete, well-staffed research and development laboratories for conducting Environmental Stress Test (EST) studies and evaluations, and a 100-year tradition of providing innovative and robust solutions in design and manufacturing. The Liquid Environmental Stress Test (LEST) machine described in this report was designed at Bell Laboratories to facilitate more rapid electronic product testing than is attainable by more traditional environmental test methods. Its unique design permits improved dynamic monitoring of product designs, and the rapid highlighting of latent production defects, such as intermittent solder joint failures.

Storage Technology Corporation: StorageTek, based in Louisville, Colorado, designs, manufactures, markets, and services information storage and retrieval systems worldwide. The company is structured into four distinct divisions: Disk Arrays (DASD), Tape Systems, Tape Libraries, and Net Work Systems Group. StorageTek is the largest provider of tape systems in the world. StorageTek has been utilizing HALT and HASS processes for 10 years, on all product lines. The Advanced Manufacturing Technology and Card Test Engineering groups were used to support this project.

Texas Instruments Incorporated: Texas Instruments Incorporated, Defense Systems & Electronics (TI DS&E) is structured into two primary operating divisions: Electronic Systems and Missile Systems. These two divisions are located in McKinney and Lewisville, Texas, respectively. The McKinney facility was utilized to perform the majority of the Texas Instruments efforts on this project. This facility houses a 1.2 million ft^2 manufacturing and test complex, which includes one of the most complete and versatile company-owned environmental test labs in the industry. This test lab consists of three test areas (climatic, dynamic, and electromagnetic) and is a fully instrumented qualification laboratory staffed by an experienced group of engineers and technicians. Other tests conducted by this group include environmental stress screening, reliability growth tests, reliability demonstration tests, and evaluation tests. Lab personnel evaluate, install, maintain, and calibrate environmental equipment purchased and used by DS&E.

Hamilton Standard, Division of United Technologies Corporation (UTC): Hamilton Standard division of UTC has three U.S. facilities that manufacture aerospace/defense electronics. They are located in Windsor Locks and Farmington, Connecticut, and in Colorado Springs, Colorado. These facilities have approximately 450,000 ft^2 devoted to the development and manufacture of advanced commercial and military electronic systems. The products manufactured at these sites include: electronic engine controls, environmental control systems, flight systems, and guidance systems. These facilities have been using traditional Military ESS (Mil-ESS) since the 1970s. Resources from all three facilities were used to support the ESS 2000 Project. Internal resources were provided by a cross-functional team of various groups including: The Manufacturing Process Technology group, which supports the development, evaluations, and transition of new process technologies to production; Product Engineering, which includes the various design functions; and production Manufacturing and Test.

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The authors would like to acknowledge the following organizations and individuals:

Hamilton Standard, Division of United Technologies Corporation

- **Ted Crouss, Wayne Korhonen, Mike Talbot**, **John Warn**, and **Len Weil**, for their contributions on various ESS evaluations.

Hobbs Engineering

- **Dr. Gregg K. Hobbs** for his work in developing the Highly Accelerated Life Test (H ALT) and Highly Accelerated Stress Screen (HASS) process and technology.

Jet Propulsion Laboratory

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Lucent Technologies

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Storage Technology Corporation

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Texas Instruments Incorporated

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Acronyms and Abbreviations

A	amp
A/D	analog to digital
AC	alternating current
ACLT	Accelerated Life Test
ACSS	Accelerated Stress Screen
Btu	British thermal unit
BIT	built-in test
C	Celsius
CAD	computer-aided design
cal	calorie
CCA	circuit card assembly
CFC	chlorofluorocarbon
cfm	cubic feet per minute
cm	centimeter
CTE	coefficient of thermal expansion
DASD	disk array storage device
DC	direct current
DOA	dead on arrival
DS&E	Defense Systems & Electronics
ED	electrodynamic
EDI	electronic data interchange
EMI	electromagnetic interference
ESS	Environmental Stress Screening
EST	Environmental Stress Test
F	Fahrenheit
FR-4	designation of the Electronic Industries Association for a fire-retardant epoxy resin-glass cloth laminate
ft	feet
ft^2	square feet
ft^3	cubic feet
g	gram
gal	gallon
g/cm^3	grams per centimeter cubed
G_{rms}	acceleration force
HALT	Highly Accelerated Life Test
HASS	Highly Accelerated Stress Screen
HP	Hewlett Packard
hp	horsepower
hr	hour
Hz	hertz
IC	integrated circuit
ICT	in-circuit test
IEEE	Institute of Electrical and Electronics Engineers
IES	institute of Environmental Sciences
in.	inch
1/0	input/output
J	joule

Acronyms and Abbreviations (continued)

JPL Jet Propulsion Laboratory

K Kelvin

kg kilogram

kW kilowatt

kV kilovolt

lb pound

LESS Liquid Environmental Stress Screen

LEST Liquid Environmental Stress Test

LN_2 liquid nitrogen

LRU line replaceable unit

m meter

m^2 square meter

Mil-ESS Military Environmental Stress Screening

min minute

MIRC Manufacturing Information Resource Center

NASA National Aeronautics and Space Administration

NCMS National Center for Manufacturing Sciences

NDF no defect found

POS proof of screen

ppm parts per million

PSD power spectral density

RELTECH Reliability Technology (to Achieve Insertion of Advanced Packaging Technology)

rms root mean square

SCSI small computer systems interface

sec second

SMT surface mount technology

TI Texas Instruments

UTC United Technologies Corporation

UUT unit under test

v volt

VASE Value Added Screening Effectiveness

W watt

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Executive Summary

Environmental Stress Screening (ESS) is an effective process for enhancing product reliability. Its purpose is to surface latent defects by stressing electronic equipment so that hidden defects or weaknesses, which can fail during normal operation in the field, are forced to fail during the screening process. ESS offers an opportunity to discover and correct product weaknesses early in the product life. The defense electronics industry has been using ESS since the 1970s, and more recently, it has been selectively applied in commercial electronics industries. With the drive towards lower product cost and even higher product reliability, more efficient and effective ways of performing ESS are being sought.

ESS 2000 was an industry collaborative project sponsored by the National Center for Manufacturing Sciences (NCMS) with the goal of identifying and evaluating cost-effective ESS processes for the 21st century. The ESS 2000 consortium consisted of the following six organizations, representing sectors of the avionics/defense, commercial, and aerospace markets:

- Hamilton Standard, Division of United Technologies Corporation (UTC)
- Texas Instruments Incorporated, Defense Systems & Electronics (T1 DS&E)
- Lucent Technologies (Bell Laboratories)
- Storage Technology Corporation (StorageTek)
- The Aerospace Corporation
- Jet Propulsion Laboratory (JPL).

Four ESS technologies/processes were evaluated and compared by this team, with the participant companies subjecting their products to the evaluations. The four ESS technologies/ processes were:

- Military Environmental Stress Screening (Mil-ESS)
- Highly Accelerated life Test/ Highly Accelerated Stress Screen (HALT/HASS)
- Electrodynamics Accelerated Life Test/Accelerated Stress Screen (ED-ACLT/ACSS)
- Liquid ESS (LESS).

Those project participants that evaluated products used their current ESS process as the baseline for comparison to the results obtained from the accelerated technologies/processes. Both the baseline data and the results achieved with the accelerated technologies/processes were included in a database which was shared with each team member. Both the cost of performing a particular ESS process and its effectiveness were evaluated. Where possible, the results were evaluated using a Value Added Screening Effectiveness (VASE) matrix. The VASE matrix process organized data by failure mode or mechanism and screening parameter to determine the cost effectiveness of a given set of stresses in detecting a given failure mode. With this information, a user can optimize the ESS process.

This study concluded the following:

- The better the understanding of the latent failure mechanisms of a product's technologies, the greater the ability to select and tailor a cost-effective screen.

- Products containing significantly greater piece part- or die-level defects than manufacturing or assembly defects were most cost effectively screened using the LESS process. On the other hand, products containing significantly greater manufacturing or assembly defects were most cost effectively screened using the HASS process. No single screening technology

appears to be the best for all products, manufacturing processes, and packaging technologies.

- Both HASS and ED-ACSS were more cost effective than Mil-ESS when the maximum throughput of the ESS chamber was used.

- Both military and commercial products can be subjected to the accelerated environments of HALT/HASS without damaging the products.

- For the products tested, exposure to the fluorocarbon fluids and rapid thermal ramp rates occurring in the LESS process did not create failures in, or change the appearance of, the products.

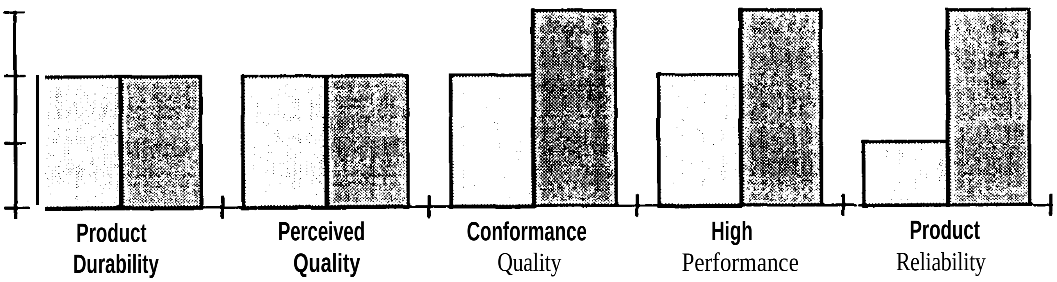
It is recommended that ESS information be collected, analyzed, and shared across the electronics industry in an ongoing collaborative process to further improve product reliability and reduce product costs.

1. Introduction

Environmental Stress Screening (ESS) originated in the space programs of the 1960s with product reliability as the ultimate objective. During the 1970s, ESS was adopted by the defense electronics industry as an effective process for enhancing product reliability. Recently, ESS is being selectively applied in commercial electronics industries, with the cost of ESS implementation also being a key consideration.

The purpose of ESS for electronic products is to expose latent defects. ESS stresses the hardware using nondestructive methods, traditionally temperature cycling and hardware vibration, to expose any component and workmanship defects. Defects are then repaired in the factory before products are delivered to customers.

A survey by Deloitte & Touche indicated a large gap in electronic product reliability between the average manufacturers and world-class manufacturers (see Figure 1-1). In addition, a Gartner Customer Requirements Survey ranked reliability as a key customer “care-about” (see Figure 1-2). Product reliability is directly impacted by ESS processes.



El Average Manufacturer   ☐ Market Leader

Source: Roth, Aleda V. and Ronald J. Chapman (1991). “Competing in the Electronics Industry Benchmarking World Class Performance.” Deloitte & Touche Research Report, San Jose, CA.

Figure 1-1. **Gaining Competitive Advantage Through Product *Quality***

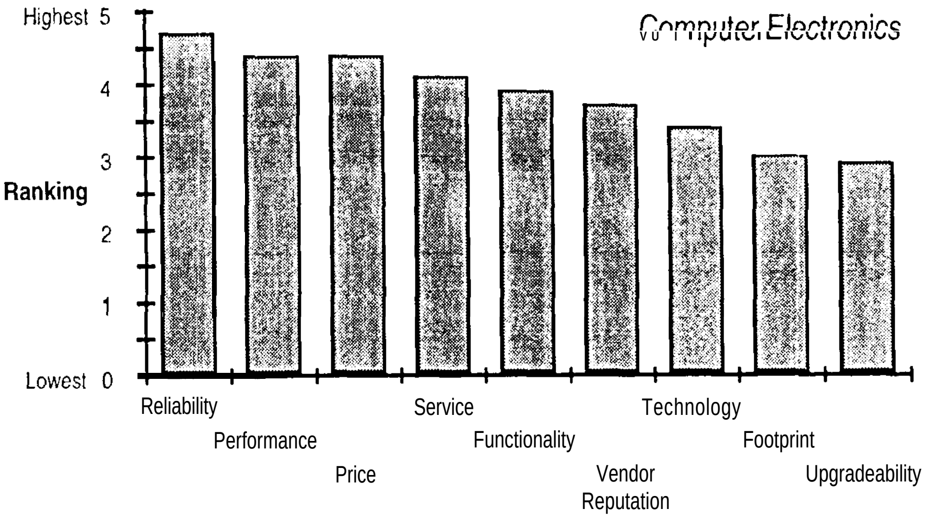


Figure 1-2. Customer Requirements Survey

1.1 Background

During the preliminary phase of this program, the participants performed literature searches through the National Center for Manufacturing Sciences (NCMS) Manufacturing information Resource Center (MIRC), conducted nonparticipant electronics manufacturers site visits, heard presentations from ESS equipment suppliers, and shared participant ESS experiences. Some of the program participants are active members of the Institute of Environmental Sciences (lES) Environmental Stress Screening of Electronic Hardware Committee, Institute of Electrical and Electronics Engineers (IEEE) Accelerated Stress Testing Technical Committee, and the government advisory board on Reliability Technology to Achieve Insertion of Advanced Packaging Technology (RELTECH).

1.2 Program Structure

The ESS 2000 Project provided a highly desired and needed mechanism to leverage the resources of a broad-based industry consortium. The team structure optimized the skills and resources of the individual participant companies (see Table 1 -1). The product diversification among the participants enhanced the ability to demonstrate dual-use (commercial/military) capability.

Representatives from the participant companies met quarterly to manage the technical, financial, and contractual performance of the project, to act on team recommendations, and to accept project deliverables. The committee members, listed in Table 1-2, also led the project activities and evaluations at their respective companies.

Table 1-1. ESS 2000 Project Participant Companies

Industry Sector	Company
Avionics/Defense	• Texas Instruments Incorporated, Defense Systems & Electronics • Hamilton Standard, Division of United Technologies Corporation
Commercial	• Lucent Technologies • Storage Technology Corporation
Aerospace	. Aerospace Corporation • Jet Propulsion Laboratory

Tab/e 7-2, ESS 2000 Project Steering Committee Personnel

Company	Individual
Texas Instruments Incorporated, Defense Systems & Electronics	Marvin J. Bellamy*
Hamilton Standard, Division of United Technologies Corporation	Charles V. DeSantis
Lucent Technologies	Ron Silver
Storage Technology Corporation	John Hess* Charles Felkins
The Aerospace Corporation	Andrew Quintero
Jet Propulsion Laboratory	Mark A. Gibbel

* Industry Champion

1.3 Technical Objectives

The objectives of the ESS 2000 Project were to compare competing ESS technologies through evaluation of these technologies using the resources of participant companies and then providing the results to the electronics industry.

The ESS 2000 Project consisted of Phases I, 11, and 111 as shown in Table 1-3.

Table 1-3, Phases of the ESS 2000 Project

Phase	Task
'base I	Established baseline for comparison of ESS echniques currently used by NCMS members. ſhe Value Added Screening Effectiveness VASE) matrix was developed during this phase.
'base II	Evaluated four alternative ESS techniques: • Military Environmental Stress Screening (Mil-ESS) . Highly Accelerated Life Test/Highly Accelerated Stress Screen (HALT/HASS) • Electrodynamics Accelerated Life Test/ Accelerated Stress Screen (ED-ACLT/ACSS) • Liquid Environmental Stress Screen (LESS). Alternatives provided a benchmark for current practices. The VASE matrix was used where possible to correlate screen effectiveness and associated costs,
'base III	Final project report and industry communication.

1.4 Technologies Evaluated

- **Military Environmental Stress Screening (Mil-ESS):** Mil-ESS uses temperature cycling and vibration stresses, which are normally applied in sequence, to precipitate latent product defects. The screen is applied at the system or line replaceable unit (LRU) level. The product is normally powered and monitored during the screen. This technology uses an electrodynamic single-axis vibration table and an air thermal chamber.

- **Highly Accelerated Life Test (HALT)/ Highly Accelerated Stress Screen (HASS):** Both HALT and HASS use a combination of rapid thermal cycling and vibration to precipitate latent product defects in less time than traditional ESS. The HALT/HASS process uses simultaneously applied stresses, which include rapid rate of temperature change thermal cycling as well as six degrees of freedom pneumatically induced random vibration. Other stresses, such as voltage and frequency margining, can also be used.

  Proponents of this technique claim a cost savings of at least one order of magnitude when compared to traditional ESS techniques. HALT is used during the product development stage to verify product robustness and to establish HASS limits; however, it can be performed again at any time to characterize equipment performance. HASS is used during the manufacturing process to verify product or process integrity. The product subjected to the HALT and HASS is normally powered and monitored during the test or screen.

- **Electrodynamic Accelerated Life Test/ Accelerated Stress Screen (ED-ACLT/ACSS):** This technology, which is similar to the HALT/HASS process described above, uses an electrodynamic single-axis vibration table and an air thermal chamber. The chamber is modified to provide rapid temperature ramp rates. The product being screened is normally powered and monitored during the screen.

- **liquid Environmental Stress Screen (LESS):** The Liquid Environmental Stress Test (LEST) machine uses an inert fluid bath for applying thermal stress to circuits. In this process, circuit card assemblies (CCAs) are immersed alternately between cold and hot baths of a fluid such as Fluorinert®. Products normally achieve thermal equilibrium with the fluid bath within 1 min. Since the product can be brought to the low--and high-temperature extremes very rapidly, a typical LESS test regimen (3 to 10 cycles) requires less than 1 hr, compared to several hours or days needed for traditional air chamber ESS.

1.5 The Database

The raw data from the ESS 2000 Project was gathered and stored in a shared project proprietary database. The database allowed standardized coding of data so that information from the various sources could be compared and analyzed. The data included: (1) failure summary reports, (2) timeline events, and (3) product and process descriptions.

The database linked data from various applications, such as Microsoft® Excel data sheets, Microsoft” Word documents, and Microsoft Access” files, which could be automatically opened from the database. The database was created with FileMaker Pm’” and was intended for the participant companies to use for future reference with the potential for accumulating new data for ongoing analyses. Block diagrams representing the processes used to evaluate each technology are supplied with the ability to “drill down” to lower level details. More information on the database is given in Section 6 of this report.

1.6 Cost Model

The ESS 2000 Project cost model was used to compare and contrast the costs of performing various stress screens. When the cost model is combined with the VASE matrix, screen attribute costs can be determined and ultimately optimized. The participants gathered cost data on their respective ESS processes. This information was combined and analyzed to compare the cost differences among the four processes. More information on the cost model is given in Section 7 of this report.

1.7 Value Added Screening Effectiveness (VASE) Matrix Process

The application of the VASE methodology and process was derived from the work being done at JPI. on physics-of-failure-based test. The VASE process was used as the method to determine the effectiveness of the LESS and HASS processes for Product 3. Application of the VASE process enabled optimization trade-offs among various design and verification activities as well as optimization of screening processes. Specifically, the VASE matrix organized data by failure mode and/or mechanism and screening parameter to determine the effectiveness of a given set of stresses (or a single stress parameter) in detecting a given failure mode and the number of those failure modes present in a design.

The output of this process is shown in the VASE application for Product 3 in Subsection 5.3. More information on the VASE process is given in Section 8 of this report.

2. Technology Overview

The four Environmental Stress Screening (ESS) technologies evaluated by the project team were:

- Military Environmental Stress Screening (Mil-ESS)
- Highly Accelerated Life Test/ Highly Accelerated Stress Screen (HALT/HASS)
- Electrodynamics Accelerated life Test/ Accelerated Stress Screen (ED-ACLT/ACSS)
- Liquid ESS (LESS).

The subsections that follow, Subsections 2.1 through 2.4, provide an overview of each of these technologies. Subsection 2.5 identifies the sample size and failure criteria applicable to these technologies and their evaluation.

2.1 Mil-ESS

Mil-ESS is defined as a process involving the application of one or more specific types of environmental stresses to a product. These stresses include air temperature cycling and random vibration. The screen is applied at the system or line replaceable unit (LRU) level. The stresses are typically applied in sequence (e.g., random vibration followed by thermal cycling or thermal cycling followed by random vibration), and on an accelerated basis but normally within product performance specification limits. Characteristics of Mil-ESS include:

- Sequential stress application
- Tailored air temperature cycling within the limits of -55° to +85°C[1]
- 5 to15°C/rnin temperature ramp rates
- Tailored number of cycles, usually in the 10 to 20 range [2]
- Tailored random vibration applied in a single axis or sequentially applied in two or three axes for a duration of 10 to 15 rein/axis [3]
- Continuous monitoring of function built-in-test (BIT).

2.1.1 Temperature Cycling

This process typically uses temperature chambers with an interior working volume from 32 ft^3 (38 in. W x 40 in. D x 36 in. H) to 125 ft^3 (78 in. W x 58 in. D x 48 in. H). The chambers have multistage mechanical refrigeration (compressor) systems for cooling and electric resistive heating elements. They provide control of temperatures usually over the range of -70° to + 170”C with ramp rates of 5 to 15°C/min.

Compressors and heaters require 480-VAC, 3-phase power, while the programmable temperature controllers require 11 O-VAC, 60-cycle power. Water is necessary for the secondary heat exchanger for rapid removal of heat from the chamber. Cornpressed air is also required to secure the removable chamber floor and to purge moisture from the chamber. Cornpressed air requires 11 0-VAC power.

2.1.2 Random Vibration

The power spectral density (PSD) can be tailored depending upon the product design. The frequency range is normally from 20 to 2,000 Hz.

[1] The temperature cycle profile is developed by reviewing the. temperature limits in the equipment specification and by performing thermal surveys to determine thermal stabilization times at each extreme. The temperature transition rate is identified by thermal survey.

[2] l'he number of temperature cycles is based on experience. with equipment of similar technology, complexity, and maturity.

[3] The random vibration profile. is developed by using vibration surveys, a review of the equipment vibration specification, and actual end-use data, Every effort was made to ensure that the profile selected would precipitate workmanship-type failures while not damaging the hardware under test.

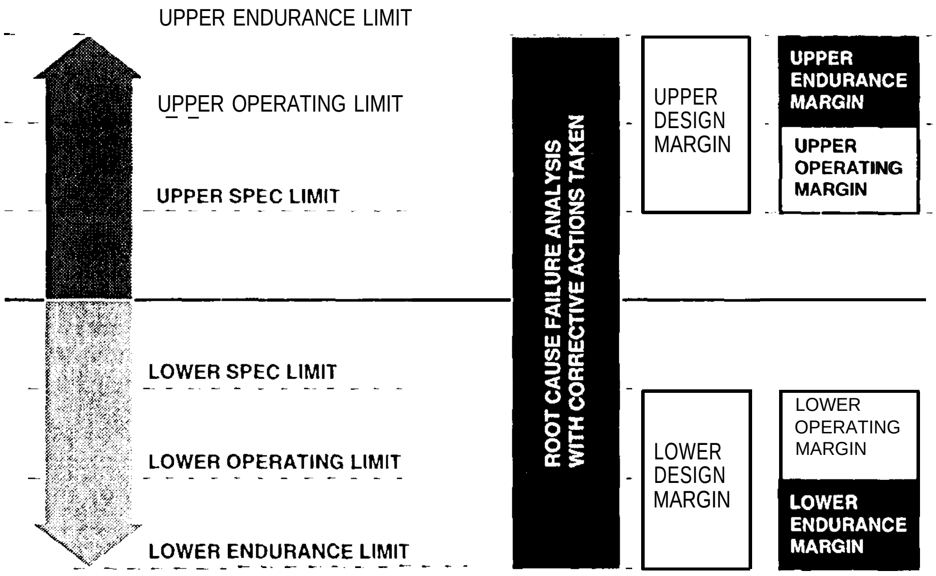


Figure 2-1. Typical HAL T Thermal Limit Process

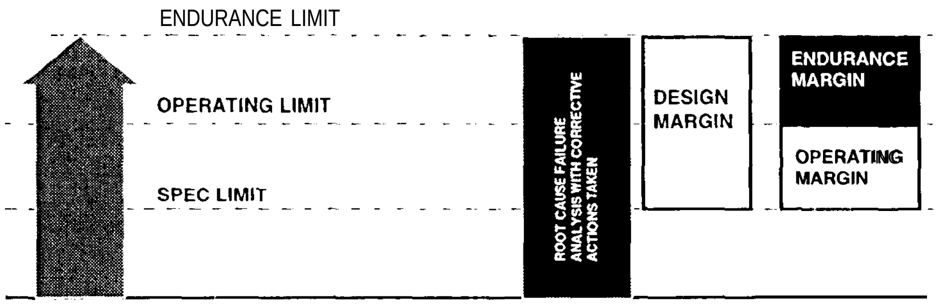


Figure 2-2. Typical HAL T Vibration Limit Process

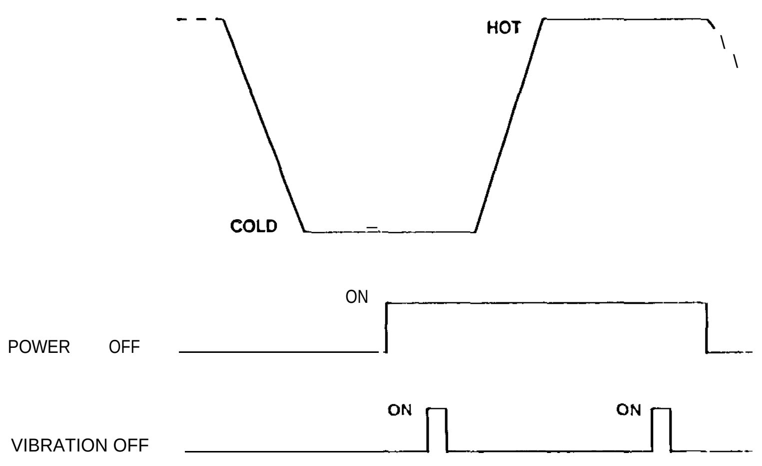


Figure 2-3. Typical HASS Cycle

- Simultaneous application of stresses
- Multiaxis random vibration
- 20° to 60 °C/min thermal ramp rates
- Power/frequency/voltage cycling
- Screen limits determined from HALT results
- Functional testing during screen.

2.2.3 Proof of Screen (POS)

POS is the process used to verify that: (1) the HASS developed for a product does not damage product, and (2) the HASS does not consume a significant portion of the product's useful life.

2,3 Electrodynamics ACLT/ACSS

2.3.1 ED-ACLT

ED-ACLT is the process in which products are subjected to progressively higher stress levels (e.g., thermal cycling, rate of temperature change, vibration, power cycling, and product specific stresses, such as clock frequency and voltage variation). These stresses are not meant to simulate field environments, but to find weak links in the design and manufacturing processes through extreme stimulation, which is well beyond the expected field environments. ED-ACLT is used during the product's design cycle to detect the inherent design weaknesses of a product so that corrective actions can be taken at the design level. The ED-ACLT process also provides product robustness data for determining an ED-ACSS. During ED-ACLT, the stress levels are incrementally increased to find the product operating limit, which is the point at which the unit under test (UUT) stops operating within its performance and product endurance limits. Typical tests performed during ED-ACLT are:

- Cold temperature limit determination
- Hot temperature limit determination
- Fast temperature cycling limit determination
- Vibration limit determination
- Combined environmental exposure.

2.3.2 ED-ACSS

ED-ACSS is the process that involves the application of combined environmental stresses (e.g., thermal cycling, vibration, power cycling, voltage margining, and clock frequency) to a product. The vibration stress is applied through a single--axis autospectrum electrodynamics vibration table. The stresses are applied on a highly accelerated basis and may exceed product specification limits. The product is stressed to precipitate to hard failure, latent or incipient defects or flaws which, if not corrected, will probably cause product failure in the use environment. The ED-ACSS profile is developed from the ED-ACLT and the POS processes.

Typical characteristics of ED-ACSS are:

- Simultaneous application of stresses
- Tailored temperature cycling within the limits of -60°to+120°C
- 15° to 60 °C/min temperature ramp rates
- May include power cycling/frequency variations/voltage variations
- User tailorable vibration autospectrum
- Random vibration applied by an electrodynamics vibration table in a single axis and applied during the temperature cycling
- Functional testing during the screen.

2.3.3 ED Proof of Screen

POS is the process used to verify that: (1) ED-ACSS does not damage the product, and (2) the ED-ACSS does not consume a significant portion of the product's useful life.

2.3.4 Key ED-ACLT/ACSS Factors

The key technology factors associated with the temperature cycling, random vibration, power cycling frequency variations, and voltage variations used in the ED-ACLT and ED-ACSS processes are described next.

2,3.4,1 Temperature Cycling

This process uses temperature chambers with an **interior working** volume ranging from 32 ft^3 (38 in. W x 40in. D x 36 **in. H) to 125** ft^3 **(78** in. W x 58 in. D x 48 in. H). The chamber has a cooling system consisting of LN_2 or a combination of complex multistage mechanical refrigeration (compressor) and LN_2 boost. Electric resistive heater elements provide heating. These systems provide control of temperatures over the range of -70° to +170°C with ramp rates of 15° to 60 °C/min usually obtained on the product being tested.

Compressors and heaters require 480-VAC, 3-phase power, while the programmable close-tolerance temperature controllers require 110-VAC, 60-cycle power. Water is also required for the secondary heat exchanger for rapid removal of heat from the chamber when compressors are used. Liquid nitrogen (LN_2) is normally required to obtain ramp rates in the 15° to 60 °C/min range on the product. The LN_2 can be supplied through a large external tank or Dewar containers near the equipment. If Dewar containers are used, a timely exchange of full Dewar containers for empty containers is necessary to keep the system in operation. If a large external tank is used, the equipment must be as close as possible to the tank to reduce the quantity of expensive vacuum tubing required and to maintain system performance. Compressed air is not normally required for purging the chamber because the LN_2 reduces the quantity of moist air in the chamber.

2,3,4.2 Random Vibration

The PSD is tailored to the product design. The frequency range is normally from 20 to 2,000 Hz with vibration applied for 10 to 15 min in a single axis (the axis perpendicular to the plane of the majority of the printed circuit boards). Vibration surveys are performed prior to the start of any screening regimen to ensure that appropriate tailoring of the PSD level over certain frequency bands is accomplished to prevent possible product damage. Electrodynarnic vibration tables are used, and once the frequency spectrum is selected for screening, it is clearly defined and repeatable.

Most of the vibration tables range from 2,000 to 18,000 pounds force and require 480-VAC, 3-phase power. Vibration table cooling of 1,000 cfm is normally required to provide heat transfer during operation.

2,3,4.3 Power Cycling and Frequency/Voltage Variations

Cycling power, varying frequency, and varying voltage may also be used to stress the UUT. The power to the UUT is sometimes turned off during the cold ramp and during part of the cold soak to expedite the transition times. Frequency and/or voltage variation and power cycling are used to increase the stresses at the piece part or die level.

2,4 LESS

The application of thermal shock is often used for detecting latent flaws or weaknesses in electronic and mechanical devices and assemblies. Success in finding these latent flaws may be related to the rate of device temperature change. Chambers that use inert liquids as the temperature-transfer medium are able to effectively produce temperature rates of change (thermal shock) in devices and assemblies that may reach 1,000°C/min. The detection of some latent defects may be related more to the high rate of temperature rise or fall than to time maintained at temperature. In addition, the rapid change in temperature permits the liquid stress test devices (CCAs) to traverse one complete temperature cycle in less than 6 rein, as opposed to typical air temperature cycle times of 20 min or longer for comparable heat loads. However, because of difficulties in removing fluid from some open or tunable components or assemblies, not all devices may be suitable for liquid temperature testing.

The Liquid Environmental Stress Test (LEST) chamber operates over a maximum temperature range of -20° to +85°C, changing fluid from hot to cold within each immersion tank, while keeping the devices under test stationary (other LEST chamber designs can operate over much wider temperature ranges with different fluorocarbon fluids). This has electrical test advantages in permitting test cables to remain shorter and fixed in place within the test chamber, because the CCAs under test remain stationary while the fluid is changed around them. Other liquid test machines have been designed to transfer their test devices back and forth between a permanently hot immersion tank and a permanently cold immersion tank, requiring sufficiently long and flexible cabling to follow all CCAs. Temperature rates of change are very similar for both types of LEST machine designs.

In the past, fluorocarbon liquids have been used for vapor phase soldering and thermal shock testing of individual components. In general, they are nontoxic, nonflammable, have a low ozone depletion potential relative to many other chlorofluorocarbons (CFCs), and are electrically inert. Because of these favorable properties, fluorocarbon liquids may be used as the heat transfer medium for liquid environmental stress testing of CCAs. The high heat capacities (0.25 g-cal/g-°C), thermal conductivities (6 to 7 x 10-9 W/cm-°C), densities (1.7 to 1.92 g/cm^3), and dielectric strengths (40 to 50 kV for a less than 1-in. gap) of these fluorocarbon fluids help to achieve a higher temperature time rate of change and a more uniform temperature distribution for *powered-up* CCAs as compared with an air medium.

2.4.1 LEST Facility

A novel LEST machine was utilized for the ESS 2000 Project.

2,4.1.1 Overview

LEST machines are designed to immerse product alternately in hot and cold liquid baths. Traditional LEST machines employ two immersion tanks, one maintained at high temperature and the other at low temperature. The product is alternately dipped in one bath and then in the other. Although very effective, this process does require that any electrical cabling connected between the product and stationary test equipment is long enough to allow movement of product between the two immersion tanks.

To minimize the cable lengths, a novel LEST machine was developed and based upon the results of fluorocarbon LEST trials on product models and knowledge of factory stress testing and throughput needs. This machine is different from other previous liquid thermal shock machines because it can accommodate a large, functionally powered product that can remain stationary during stressing. Either tank may be used individually for testing because the product remains stationary while the hot and cold liquids are interchanged within one or both of the two immersion tanks. The new LEST machine has the advantage of easier communications with external test sets. Its thermal performance is essentially identical to older, traditional two-tank LEST machines.

For the ESS 2000 Project, product placed into the LEST machine consists of CCAS with active and passive components and metal fixturing with card guides to support and align the cards. A common backplane may also be attached to allow for communications between the cards via cables and interconnection paths within the backplane itself. External cabling is used to communicate with a test set outside of the LEST machine.

The LEST machine, shown schematically in Figure 2-4 and with close-up details in Figure 2-5, has the following:

- Accommodations to easily connect test fixtures to external test equipment so that products may be electronically tested during thermal cycling
- Two separate test chambers (tanks), each of which may be used independently to alternate the thermal cycle of individual batches of CCAs. Thus, while one chamber is being

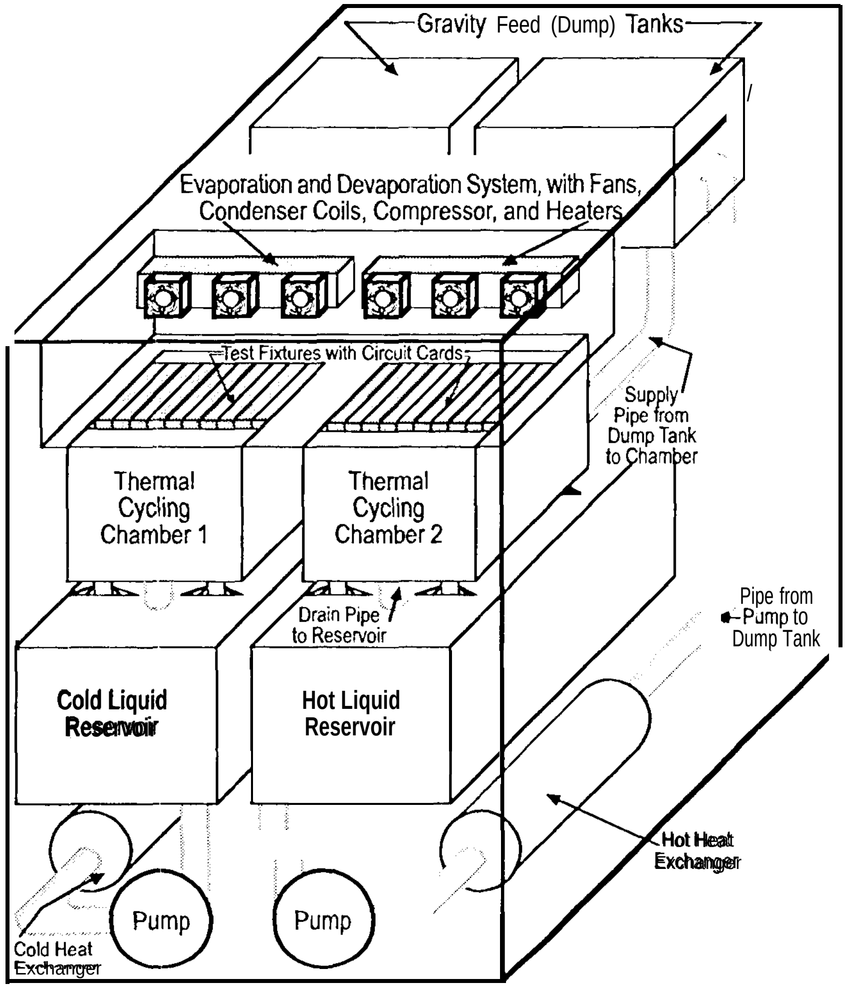
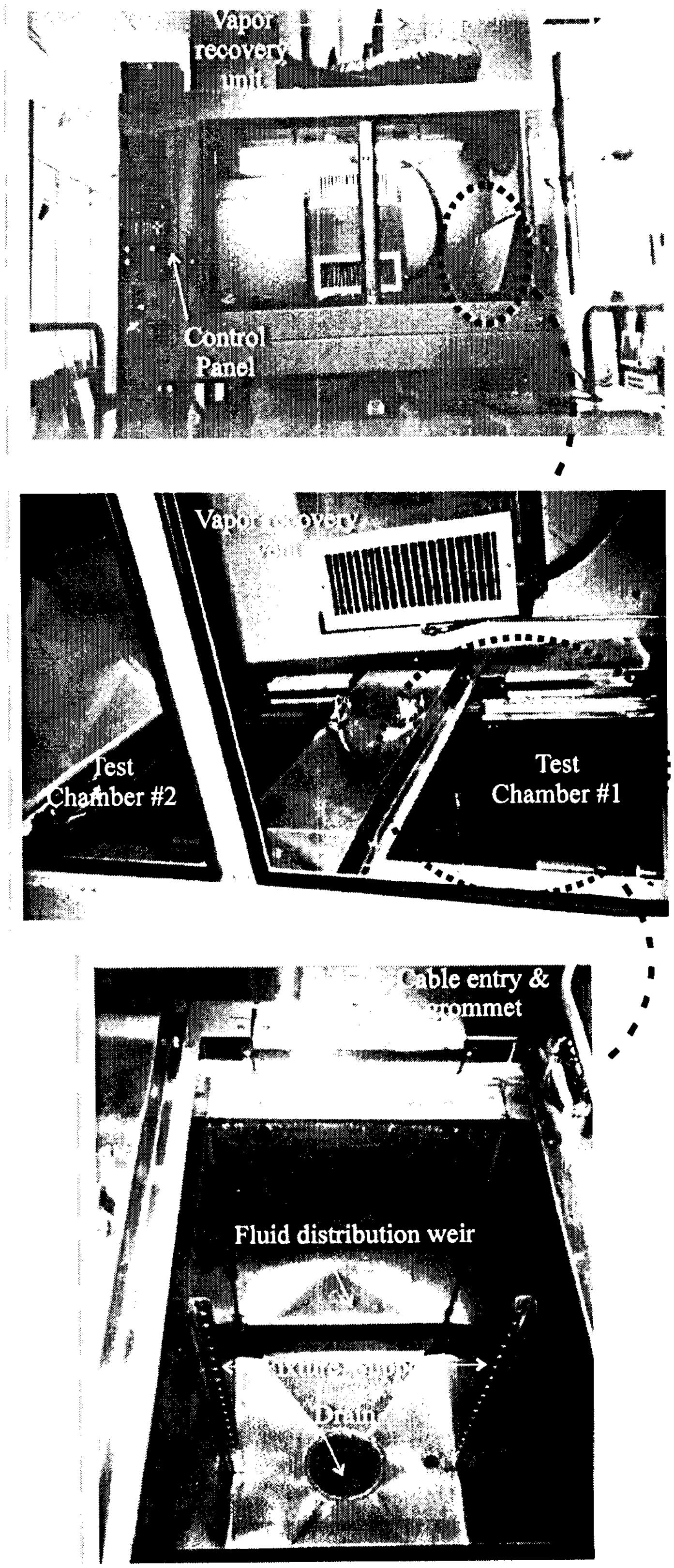


Figure 2-4. LEST Machine Overall Schematic

thermal cycled, a fluorocarbon vapor recovery process and test fixture unloading and reloading can take place in the other chamber. The working volume of each chamber is 20 in. x 19 in. x 13 in.

- Test fixtures that allow individual CCAS to be conveniently loaded and unloaded, and alignment bars attached to the insides of the test chambers for easy adjustment of the test fixture positions.
- A system for thermal cycling of the electronic product by alternately pumping hot and cold fluid into and out of one of the test chambers at a time, while the second chamber is being loaded or unloaded. This is done by using separate hot and cold liquid reservoirs with associated plumbing and fluid controls to the two test chambers. The two test chambers can then alternately stress the product.
- Controls for maintaining the working fluid at the target test temperatures and for providing continuous convection of the working fluid around the product in the test chambers to enhance heat transfer.
- Design features to prevent a significant loss of fluorocarbon from the machine including:
  - Minimization of hot fluid vapor loss
  - Prevention of drag-out of working fluid at the end of the thermal cycling regimen by drying the product, test fixture, and chamber prior to unloading
  - Prevention of direct fluid losses due to drips, spills, etc., during operation.



a. Front View

b. ***Interior*** View

c. **Top View of One** ***Chamber***

Figure 2-5. General and **Close-Up Views Showing LEST Machine Features**

- Mcans for removing contaminants from the machine, including removal of
  - Water and/or ice from the fluorocarbon
  - Flux residues from the fluorocarbon
  - Any additional contaminants that might damage the product or degrade the performance of the facility.
- Features to provide for safe operation of the machine, including protecting operators from:
  - Exposure to excessively hot surfaces
  - Breathing potentially harmful machine fumes.

2,4.1.2 **Temperature Drift Between Immersions**

The CCAS spend a short (approximately 30 see) period in air between each hot and cold immersion (see Figure 2-6). During this period when the card components are not held at temperature by the fluid, there may be a small increase in their temperature after cold immersion and before hot fluid contacts the CCAs. Alternatively, at the end of the hot immersion and before the entrance of cold fluid, passive components will experience a small drop in temperature, while active components may experience an increase in temperature. The amount is strictly determined by the amount of power being dissipated by these components during the "in-air" period.

This effect is true for all LEST machines, and acts to decrease the effective thermal shock step size, but dots not appear to affect the thermal shock ramp rate.

A nominal test procedure that would be performed on electronic CCAS using a LEST machine is shown in Figure 2-7.

After the product has been thermally cycled and before it is unloaded from the machine, liquid entrained in the CCAS and the test fixture must be removed by evaporation and reclaimed through a vapor recovery system. The fluorocarbon vapor pressure present within a test chamber's interior must be largely reduced before any reload or unload operation is performed. A typical ambient and dew point temperature profile for an LEST machine test chamber is shown in Figure 2-8. An initially high fluorocarbon vapor pressure is followed by gradual reductions in vapor content as the air stream is first drawn through a chiller for vapor condensation, then a heater to promote fluid evaporation, then returned to the test chamber. In this LEST machine design, the vapor recovery function may be performed in one test chamber while liquid thermal cycling is being applied to CCAS in the other test chamber (see Figure 2-9).

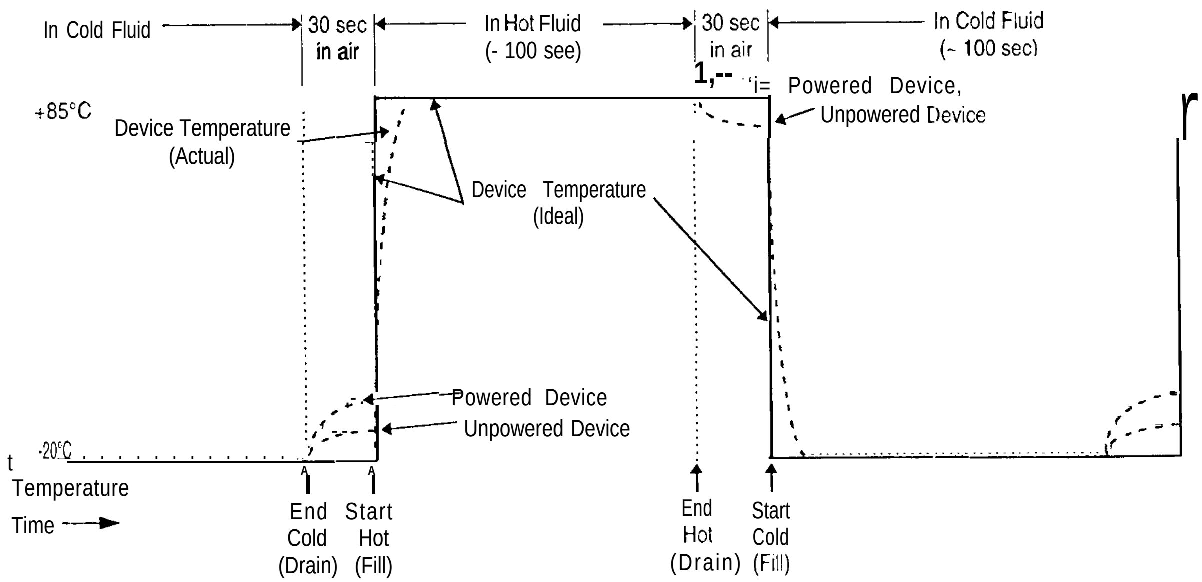
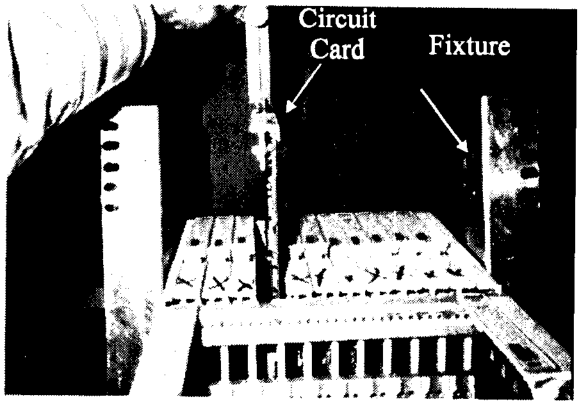
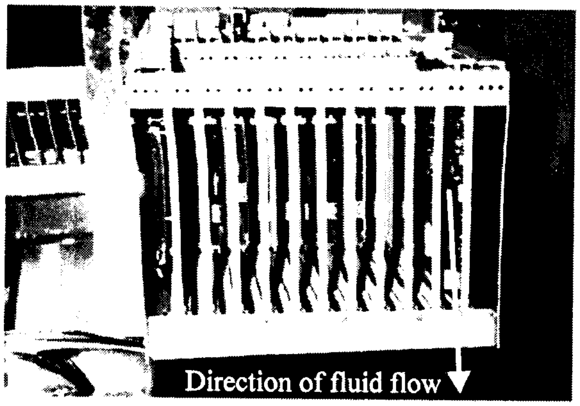


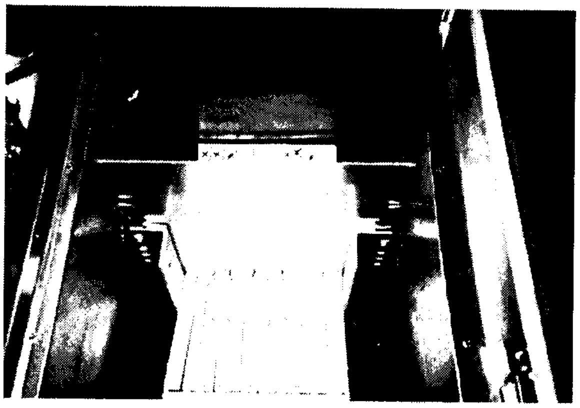
Figure 2-6. **LESS** *Temperature/Time Profile*



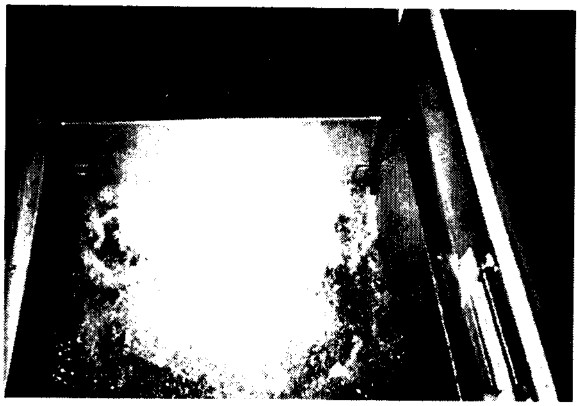
(1) Circuit cards are loaded individually into fixture.



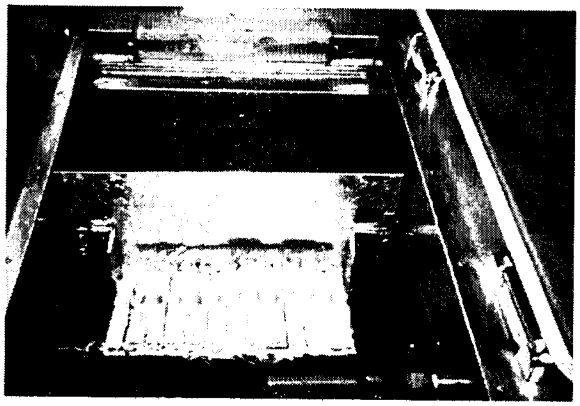
(2) When all circuit cards have been loaded into fixture, they form channels through which fluid will flow.



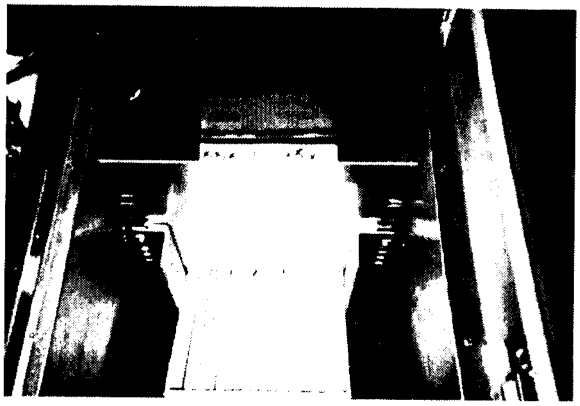
(3) Fixture is placed into test chamber in the liquid thermal shock machine.



(4) Fluid at one temperature extreme rapidly fills the test chamber to thermally shock circuit cards.



(5) Fluid flows continuously over fixture until circuit cards reach steady state temperature.



(6) Fluid rapidly drains from test chamber before fluid at other temperature extreme is allowed to fill.

Figure 2-7. Nominal Test Procedure on Circuit Card Assemblies Using a LEST Machine

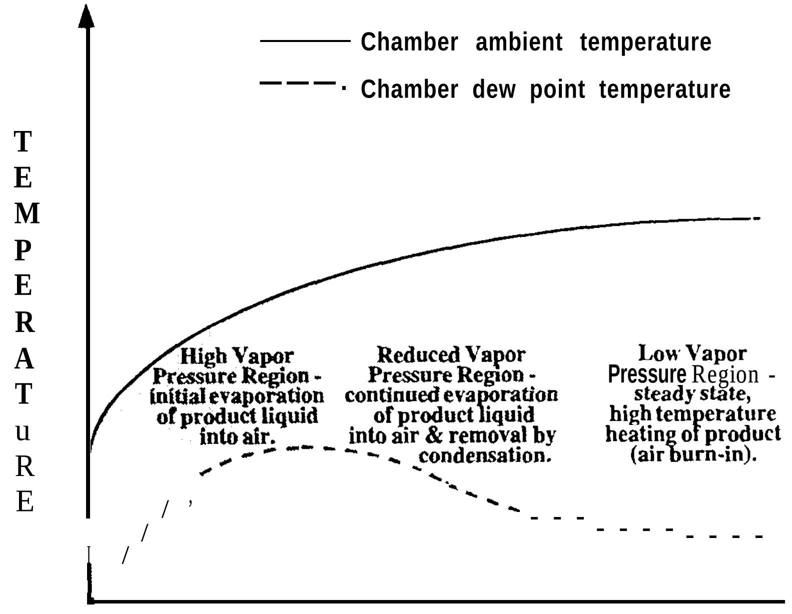


Figure 2-8. Typical *Dew Point Versus Temperature Curve for LEST Machine*

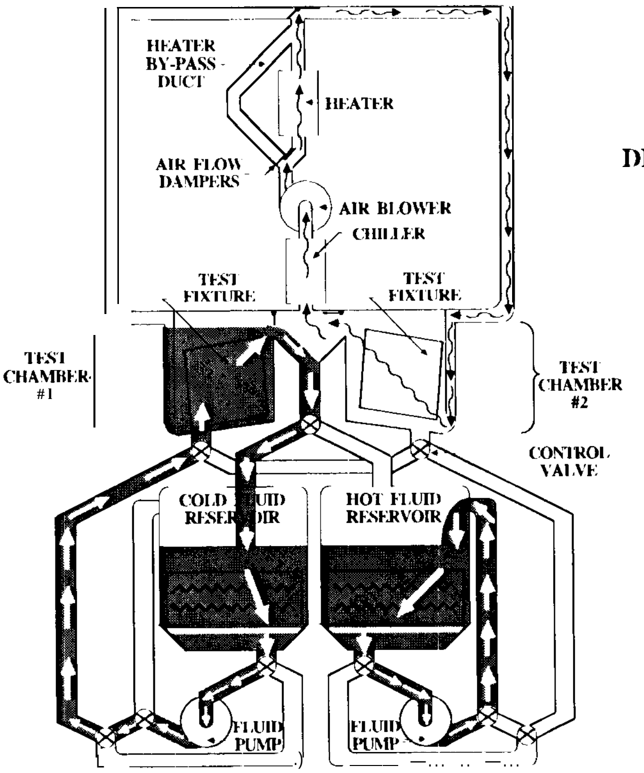
2.4.2 LESS/LEST Considerations

LESS offers advantages to manufacturing and design personnel because of its unique capabilities, but it also carries some constraints that limit its applicability to some applications. In making the decision of whether to adopt the liquid environmental stress test, three factors must be considered:

1. Compatibility: LESS is most applicable where the fluid can be circulated around the piece parts, as in CCA screening, and can be easily removed by air drying,. The compatibility of the electronic components on a CCA with the fluorocarbon fluid must be determined when considering LEST during product design. The CCA should not contain any materials that can be damaged by the fluid itself nor any open devices that may entrap the fluid and become detuned or inoperative even after LEST has been completed. If these conditions do not exist (e.g., many digital cards), then the CCAS are candidates for LEST/LESS.

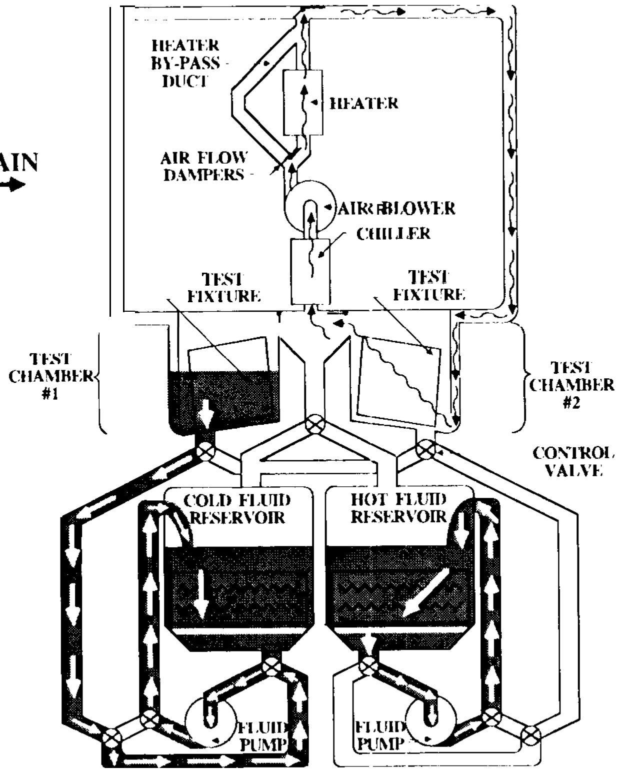
2. **Time Allocated to Complete Environmental Stress Test (EST):** The time allocated to complete EST within the overall production schedule may influence the choice bet ween air and liquid EST. LEST may offer time advantages because of its shorter cycle times required for thermal shock testing. In addition, LEST may obviate the need for vibration testing under some conditions. If this is true, then costs associated with providing custom vibration fixtures for specific CCAS maybe avoided.

3. Capital Funding Available for Initial Start-Up: Capital funding available for initial start-up of EST facilities may influence the choice between air and liquid EST. High-volume air or vibration chambers may be comparably priced with larger LEST machines, while small air or vibration chambers may cost less than smaller LEST machines. An analysis of initial costs versus savings in EST costs must be made for each application to determine the appropriate choice between air and liquid.

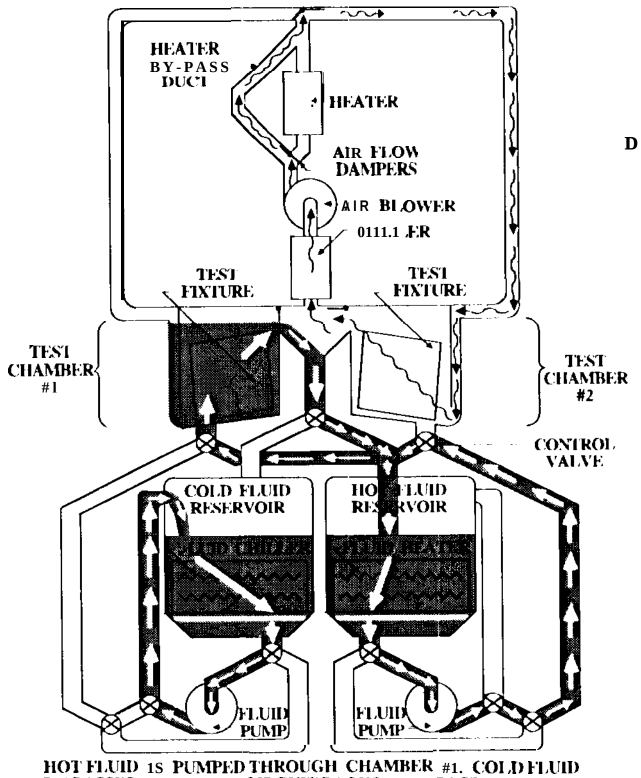


COLD FLUID IS PUMPED THROUGH CHAMBER #1. [01 FLUID BY-PASSES CHAMBERS. FLUID IS RECOVERED FROM CIRCUIT PACKS & TEST FIXTURE IN CHAMBER #2 (FLOW IN HEATER).

DRAIN →

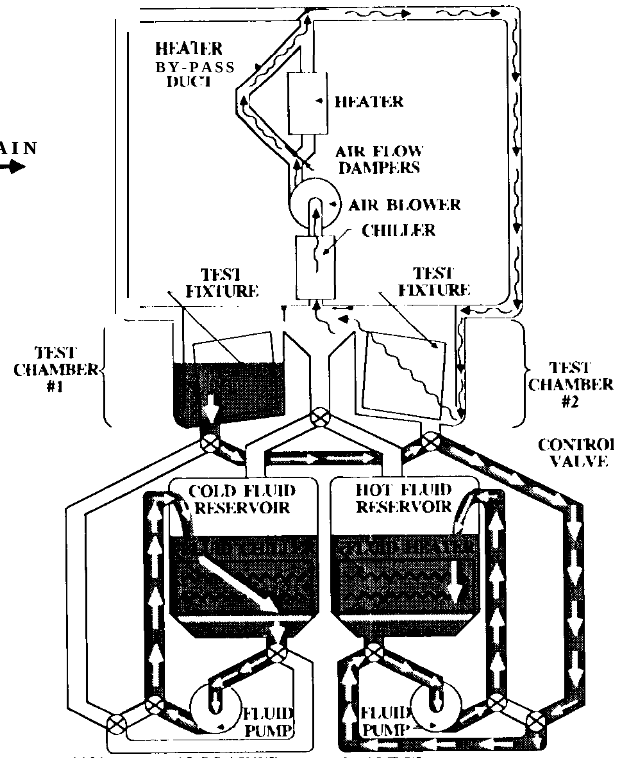


COLD FLUID IS DRAINELI FROM CHAMBER #1. 1101 FLUID BY-PASSES CHAMBERS. FLUID IS RECOVERED FROM CIRCU11 PACKS & TEST FIXTURE IN CHAMBER #2 (FLOW IN HEATER).



HOT FLUID IS PUMPED THROUGH CHAMBER #1. COLD FLUID BY-PASSES CHAMBERS. CIRCUIT PACKS AND TEST FIXTURE IN CHAMBER #2 ARE COOLED OFF (AIR BY-PASSES HEATER).

DRAIN →



1101 FLUID 1S DRAINED FROM CHAMBER #1. COLD FLUID BY-PASSES CHAMBERS. CIRCUIT PACKS AND TEST FIXTURE IN CHAMBER #2 ARE COOLED OFF (AIR BY-PASSES HEATER).

Figure 2-9. LEST Machine Liquid and Air Vapor Recovery Flow Sequences in summary, material compatibility, product volume, EST schedule, and initial capital funding considerations help to decide when LEST is the appropriate choice for production and design environmental stress testing.

2.5 Sample Sizes and Failure Categories

The alternative ESS technologies were compared on three different products:

- Product 1 was a low-volume production military product
- Product 2 was a low-volume production commercial aerospace product
- Product 3 was a high-volume commercial product.

The sample size of assemblies used in the evaluation is shown in Table 2-1. A list of relevant board technologies tested is presented in Appendix A. The failures found during the screens and subsequent failure analyses were categorized by failure mode or mechanism to allow comparisons between ESS technologies. Table 2-2 presents the categories and the definitions of each.

Table 2-1. Sample Sizes in the Evaluation

Description	Technology	Product 1	Product 2	Product 3
Tests	**Liquid ESS (LESS)** Safety of Screen	7 CCAS	2 CCAs	24 CCAS
	HALT	5 CCAS and 1 Box*	2 CCAS	**
	Proof of Screen (POS)	1 Box'	1 CCA	**
	Electrodynamics ACLT	—	1 CCA	—
	ED-Proof of Screen	—	1 CCA	—
Screens	Military (Mil)-ESS	20 Boxes*	34 CCAS	—
	HASS	6 Boxes*	—	3661 CCAS
	ED-ACSS	—	20 CCAS	—
	LESS	24 CCAS	—	1555 CCAS

*Product 1 Box contains four circuit card assemblies (CCAs)
"HALT and Proof of Screen were run prior to the ESS 2000 Project

Table* 2-2, CCA *Failure Manifestation Categories

Term	Definition
DOA	Dead on arrival—Product does not function properly upon power up and first functional test.
Margin	A failure of the product that occurs repeatedly at set environmental conditions, These environmental conditions are generally temperature and voltages, independently or in combination. Other environmental conditions result in the proper operation of the product. The failure is typically detected with a function test
Precipitated	A failure of the product that occurs as a result of environmental conditions. After precipitation of the failure, the failure tends to occur at environmental conditions less extreme than the precipitating conditions. The failure is typically detected with a functional test.
Margin - No Defect Found (NDF)	A failure of the product that occurs repeatedly at set environmental conditions, These environmental conditions are generally temperature and voltages, independently or in combination. Other environmental conditions result in the proper operation of the product. The failure is typically detected with a function test, Upon subsequent failure examination, the product failure is undetectable.
Precipitated (NDF)	A failure of the product that occurs as a result of environmental conditions, After precipitation of the failure, the failure tends to occur at environmental conditions less extreme than the precipitating conditions. The failure is typically detected with a functional test. Upon subsequent failure examination, the product failure is undetectable.
NDF	Upon failure examination, the product failure is undetectable. Additional analysis of the failure leads to the conclusion that the failure is an invalid random occurrence,

3. Technology Evaluation: Highly Accelerated Life Test (HALT)/ Highly Accelerated Stress Screen (HASS)

HALT/H ASS technology evaluation compared a baseline Military Environmental Stress Screening (Mil-ESS) process to the HALT/HASS process. The objective was to determine if military hardware can be subjected to the accelerated environments of HALT/HASS without damaging product and whether or not HALT/HASS was a more cost-effective screen.

The HALT/HASS process required that a HALT and Proof of Screen (POS) be performed on representative samples of each assembly that was being considered for HASS. These tests were performed on small sample sizes. Once the tests were complete, the samples were considered non-deliverable assemblies. HASS, like Mil-ESS, was performed on production-deliverable assemblies.

The evaluation began by collecting data on Product 1 Mil-ESS baseline boxes. Next, Product 1 circuit card assemblies (CCAs) were subjected to HALT. Following the CCA HALT, one Product 1 box was subjected to HA1 .T and then POS. Finally, Product 1 boxes were subjected to HASS. Data from the HASS process was then compared to the Mil-ESS process. The manufacturing flow diagram for the test samples is shown in Figure 3-1 and is the same for both the Mil-ESS and the HALT/HASS samples.

In the following subsections, the HALT and POS evaluations are discussed first, followed by Mil-ESS and HASS.

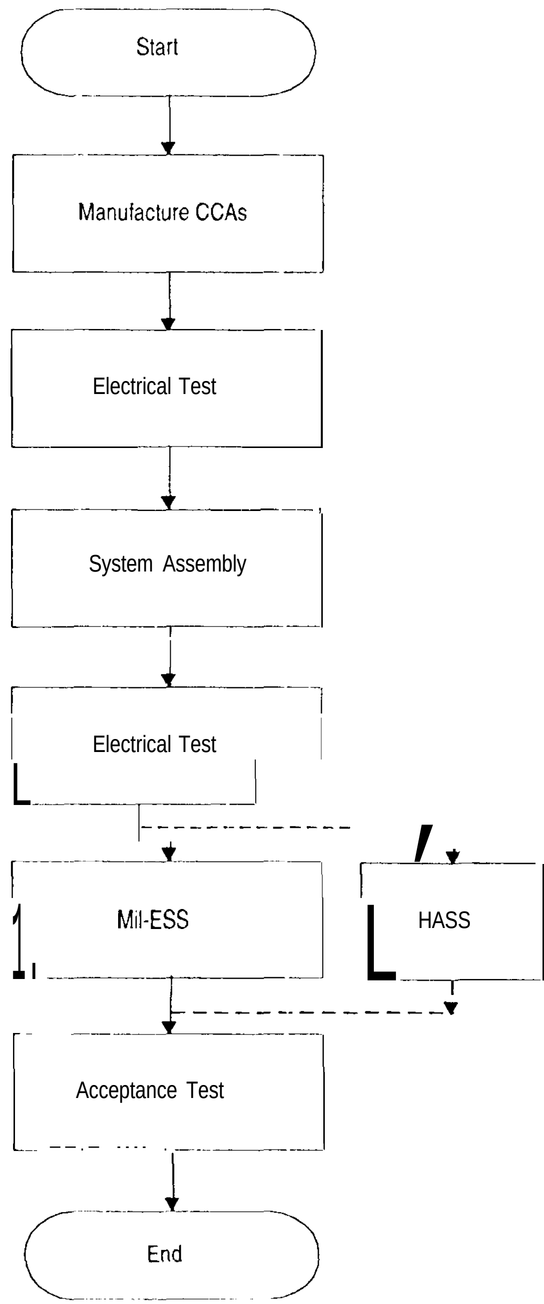


Figure 3-1. Product 1 Manufacturing Flow Diagram

3.1 HALT

HALT was performed on five Product 1 CCAS and one Product 1 box.

3.1.1 HALT Thermal and Vibration Process

HALT thermal and vibration tests were performed by step-stressing the test sample until operational and endurance limits were reached or until levels were achieved that provided sufficient design margin. The step-stress levels used for this evaluation are shown in Figures 3-2 and 3-3.

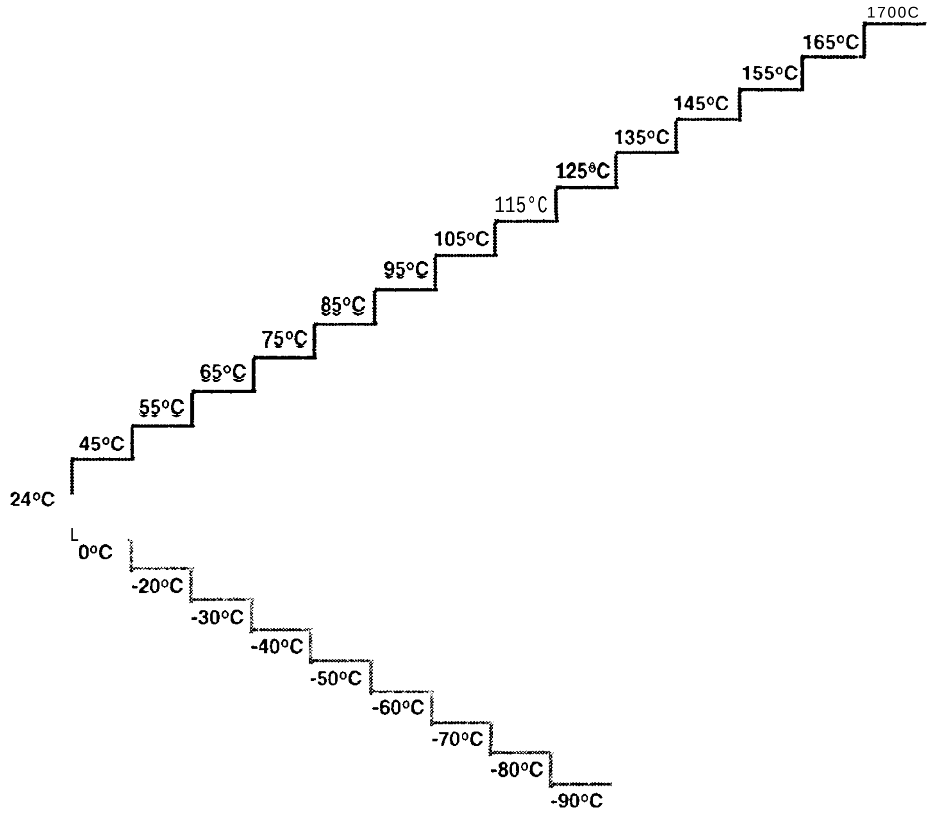


Figure 3-2, Therms/ Step-Stress Levels

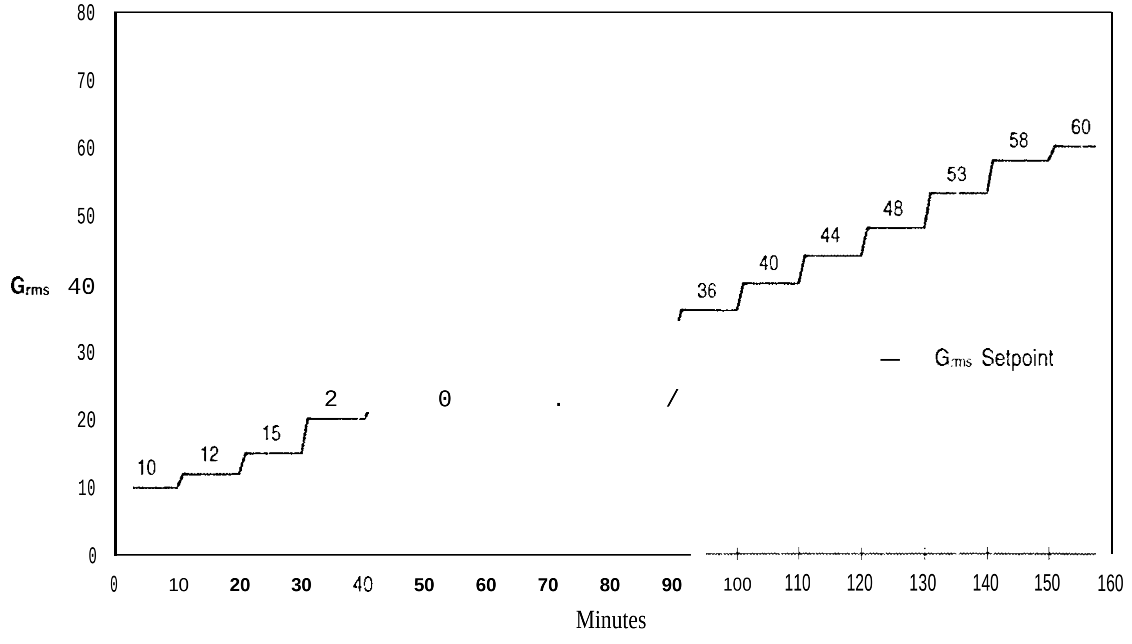


Figure 3-3. Vibration Step-Stress Levels (Z-axis)

3.1.2 Fixtures

The fixtures that held the CCA test samples consisted of an engineering box level housing. For thermal cycling only, the housing was placed on the table top as shown in Figure 3-4. For vibration only, or combined thermal/vibration, the box was mounted directly to the vibration table with two unistrut bars and four all-thread 3/8-in. rods with locking nuts, as shown in Figure 3-5.

The CCA was inserted into its mounting slot in the housing and locked down with CCA locking wedges (see Figure 3-4). Box level testing used the same fixturing technique (see Figure 3-5).

3.1.3 Test Procedures

The subsections below describe the procedures followed to conduct the chamber thermal and vibration surveys and product limit determinations.

3.1.3.1 HALT Chamber Thermal Survey

A thermal survey of the chamber (with no product installed) was performed using 40 type-T thermocouples. Sixteen of the thermocouples were located on an 8 x 8-in. grid located 6 in. above the chamber floor. The second 16 thermocouples were on the same grid, located 18 in. above the chamber floor. The last 8 thermocouples were on a 16-in. grid located 24 in. above the chamber floor. The survey was conducted bet ween temperature extremes of + 100° and -65°C with a 3-min soak at each extreme. The thermocouple readings were recorded with a Fluke Data Logger at 30-sec intervals.

3.1.3.2 HALT Chamber Vibration Survey

The layout of the chamber vibration table is shown in Figure 3-6; circled numbers indicate the 81 mounting holes. A survey of the amplitude verses frequency response on the table was performed using four Endevco 2228C triaxial accelerometers and a GenRad 2552B Vibration Controller/Analyzer. Measurements were made at 20 points covering an 8-in. grid of the table surface; labels P1 to P20 on the figure show the. location of these points.

The analysis was conducted over a frequency range of 6.25 to 5,000 Hz using 800 spectral lines of resolution resulting in a spectral bandwidth of 6.25 Hz. Measurements of all three orthogonal axes were made with the following axis definitions:

- Z-axis oriented normal to the planar surface of the vibration table
- Y-axis oriented along the surface of the table from chamber side to side
- X-axis along the surface of the table from chamber front to back.

Each triaxial accelerometer was mounted on top of a 3/8-in. by 16-thread hex head bolt that was screwed into the mounting holes of the table and locked in place with a 3/8-in. nut. The bolts were uniformly torqued to a minimum of 25 ft-lb.

3.1.3.3 Cold Thermal Limit Determination

The cold temperature limit test began with the unit under test (UUT) being run at room temperature to test diagnostics. The temperature was then stepped down to O°C and held at that temperature for 10 min minimum, and the UUT was again tested to verify proper operation. The temperature was then dropped in 10°C increments until the endurance limit of the UUT or the lower chamber temperature limit was reached, Whichever occurred first.

3.1.3.4 Hot Thermal Limit Determination

The high temperature limit test began with either the UUT being run at room temperature to test diagnostics or by proceeding directly from the cold limit determination. The temperature was then stepped up to +45°C and held at that temperature for 10 min minimum, and proper operation of the UUT was determined. The temperature was then stepped up in 10°C increments to +170°C or until the product upper operational or endurance temperature limits were reached.

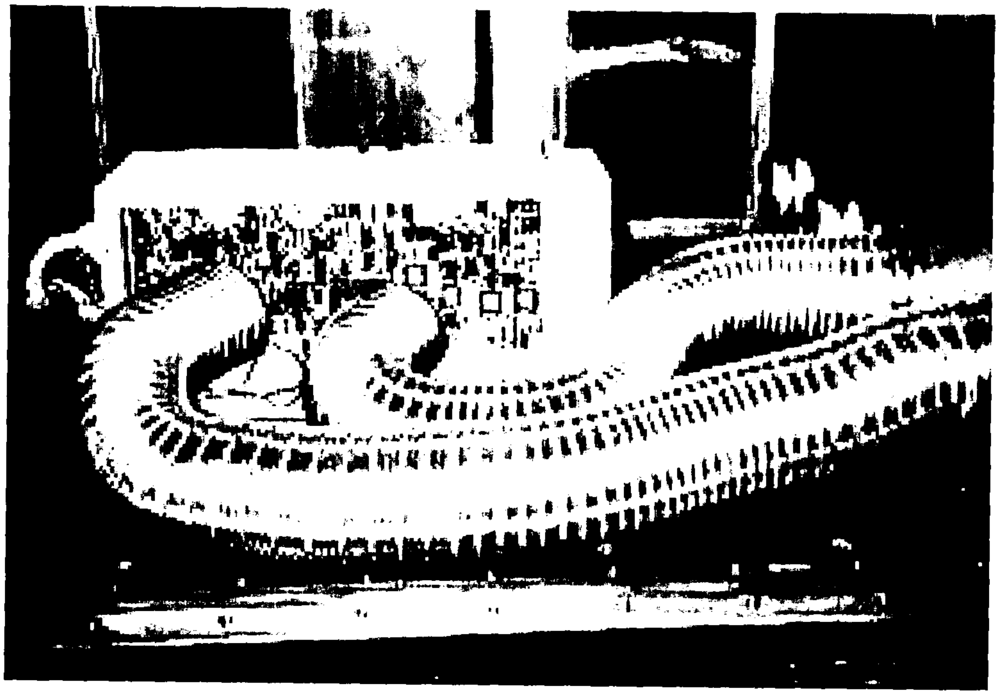


Figure 3-4. Product 1 Fixture – Thermal Tests Only

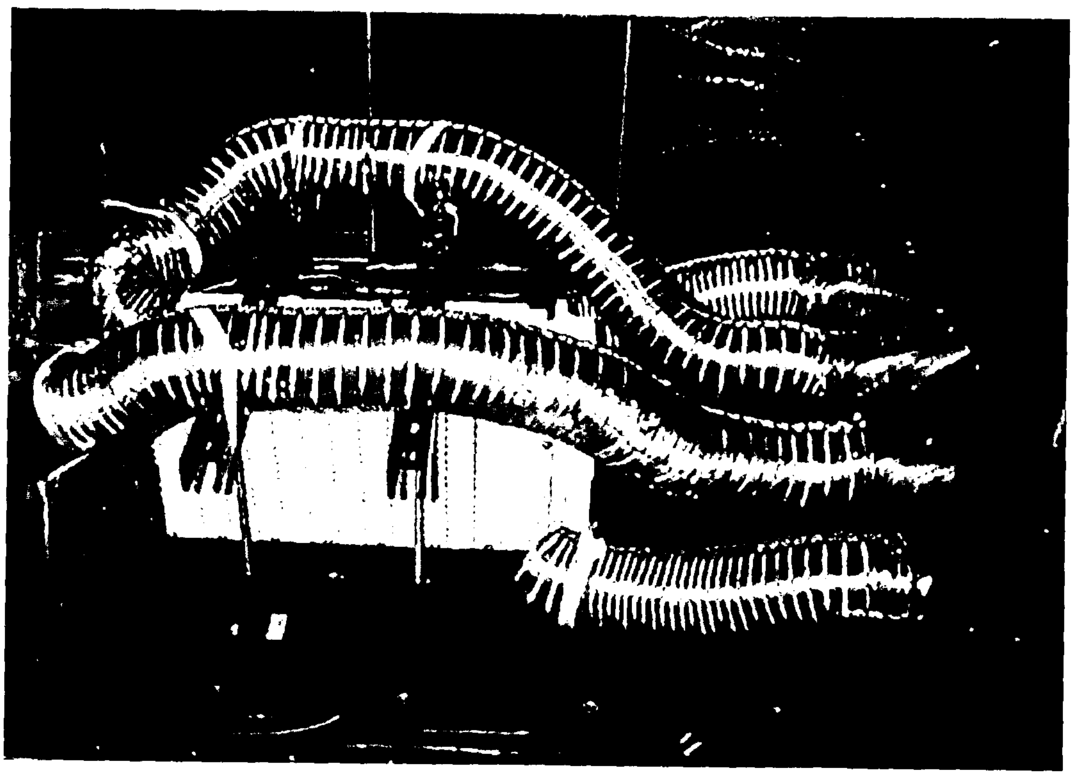


Figure 3-5. ***Product 1 Fixture – Thermal/Vibration Tests***

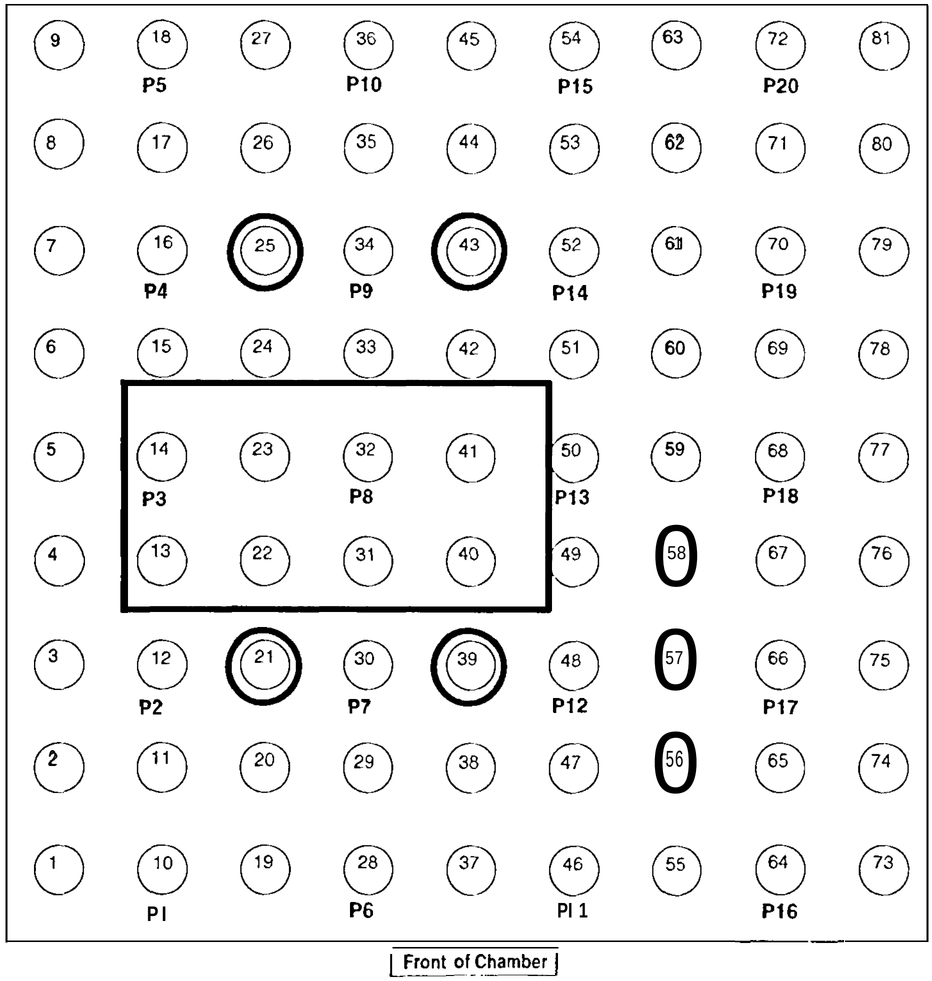


Figure 3-6. Vibration Table Mounting Points (Accelerometer Positions P1–P20)

3.1.4 Test Configuration and Equipment

HALT and HASS were all performed using a hot-mock-up configuration. Each test or screen was run with a complete and fully operational system. The test sample was placed inside the chamber and connected to the remainder of the system outside the chamber with interconnecting cables.

A QualMark model OVS-3 chamber was used for the HALT/HASS evaluations. This chamber uses liquid nitrogen (LN_2) for cooling and electric resistive elements for heating. Vibration is applied with pneumatic vibrators.

3.1.4,1 Test Sample Monitoring

Monitoring was performed by operating the test sample and observing its response. The test set and hot-mock-up system automatically monitored the product for failures through built-in test (BIT) circuitry. Visual observations were also made.

3.1.4.2 Failure Criteria

Any failure of the hot-mock-up system to perform to its requirements set a BIT fault flag. Any visually observed incorrect system response was also recorded as a failure.

3.1.5 HALT Results

- **Chamber Thermal Survey:** The chamber survey was performed without product installed to observe thermal stability of the chamber at various temperatures. Survey results are given in Table 3-1.

Table *3-1. Temperature Data Summary*

Chamber Input Temperature (°C)	Average Response Temperature (°C)	Extreme Response Temperature (°C)
“0°	+102	+98 to +105
+50	+54	+51 to +58
0	-6	-29 to +6
-50	-41	-64 to -18

Product was then installed in the chamber and the product response data was obtained to determine the temperature cycling limits for the product.

- **Chamber Vibration Survey:** As shown in Figure 3-7, the vibration across the table is not uniform; therefore, a HALT performed at one point on the table may not result in the same product response at another point on the table. As a result, the POS and subsequent HASS must be performed at the same point with the same product orientation.

3.1.6 Product 1 CCA and Box Results

Product 1 HALT was performed using engineering CCAs, which proved to be very robust.

Operational limits ranged from +95° to +130°C on the hot side, and from -65° to -90°C on the cold side. The endurance limits could not be found for the cold side due to the limits of the chamber. The hot endurance limits ranged from + 150° to +170°C. Box level operational limits ranged from -65° to +85°C and endurance limits ranged from -75° to +120°C.

3.2 Proof of Screen

The POS is used to verify that the HASS regimen, established during HALT, does not damage the product. To gain this confidence, a test sample was repetitively subjected to the HASS cycle (Figure 3-8) until it had accumulated cycles totaling one order of magnitude greater than the HASS requirement without failure. The HASS requirement in the Product 1 evaluation was four HASS cycles, therefore 40 cycles was the target POS.

3.2.1 Fixtures

The fixture used for POS was the same as for HALT described in Subsection 3.1.2. A POS was performed on one Product 1 box sample.

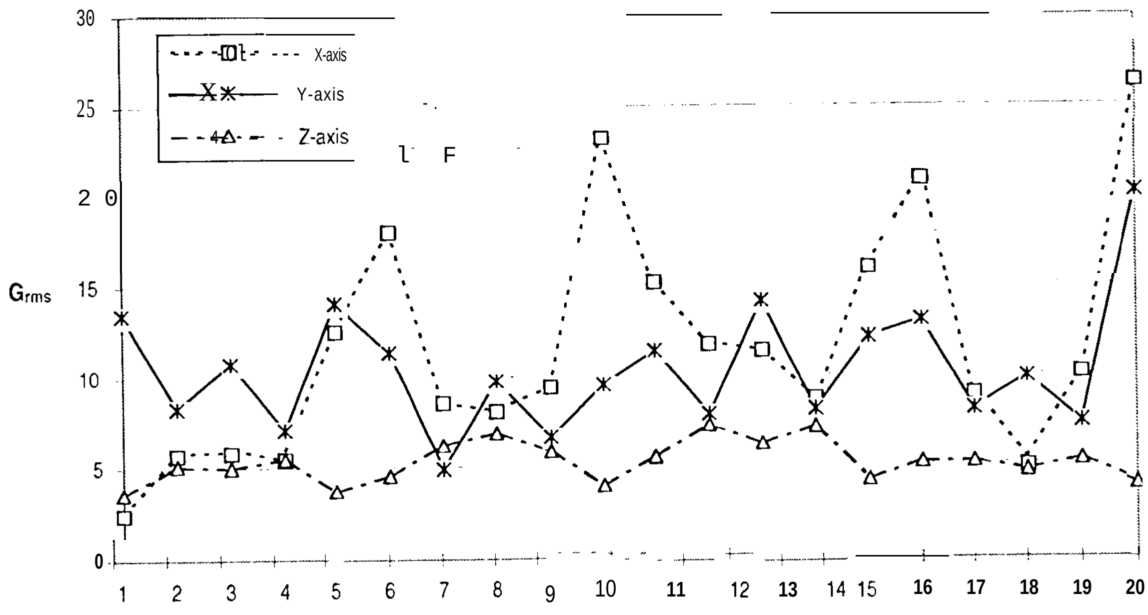


Figure 3-7. ***Vibration Survey Summary of Table Response***

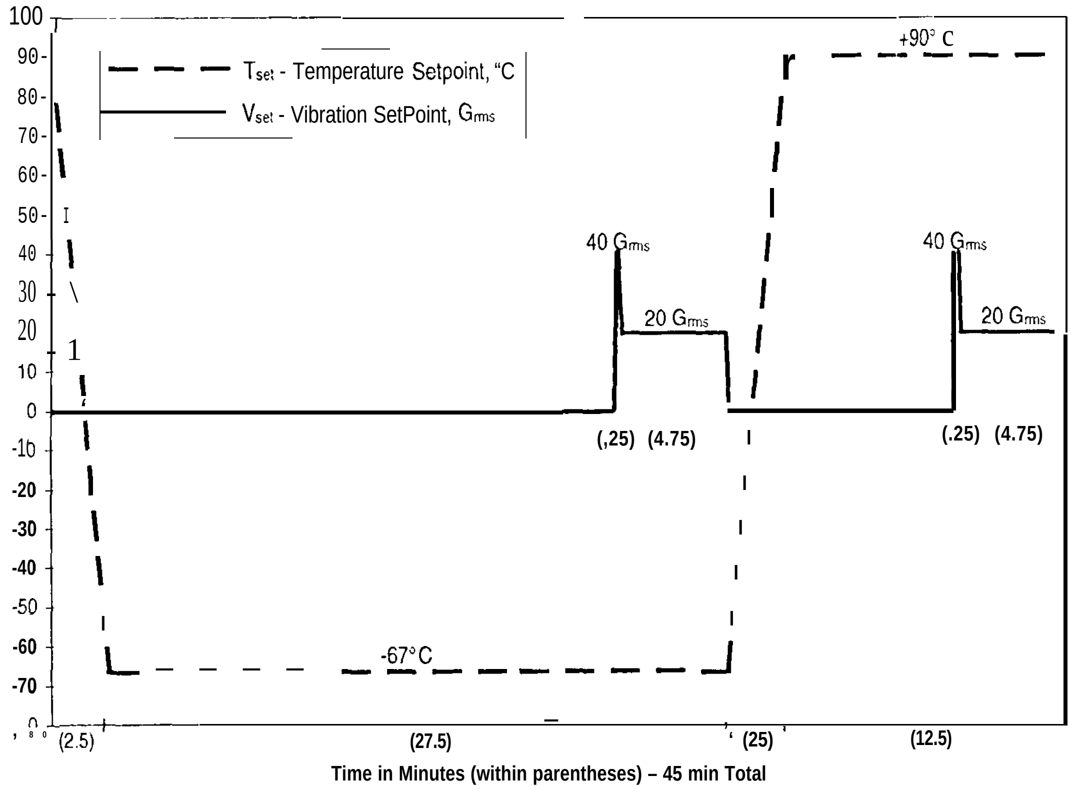


Figure 3-8. Single HASS/POS Cycle Used on Product 1 Box

3.2.2 Test Configuration and Equipment

The test configuration and equipment used for POS were the same as for the HALT described in Subsection 3.1.4.

3.2.2.1 Test Sample Monitoring

Test sample monitoring was the same as for the HALT described in Subsection 3.1.4.1.

3.2.2.2 **Failure Criteria**

The failure criteria was the same as for the HALT as described in Subsection 3.1.4.2.

3.2.3 POS Results

A Product 1 box POS was performed using the HASS cycle illustrated in Figure 3-8. Of the four CCAS in the box, one had also been subjected to HALT prior to performing the POS. This CCA failed after 35 HASS cycles. No other failures were experienced. Since all of these CCAS were repaired engineering assemblies and the one failure that occurred was on a CCA that had also been subjected to HALT, it was concluded that four cycles of HASS should not damage product.

3.3 Mil-ESS Process

The requirement for the baseline Product 1 box screen was to complete 10 min of random vibration (box is nonoperational) in the axis normal to the CCAs followed by four thermal cycles, with the last two failure-free. Each of the four cycles was 6 hours in duration, The vibration and thermal profiles are shown in Figures 3-9 and 3-10.

3.3.1 Fixtures

The vibration fixture used for the Mil-ESS process on Product 1 is shown in Figure 3-11.

3.3.2 Sample Size

The sample size for the Product 1 Mil-ESS evaluation was 20 production boxes.

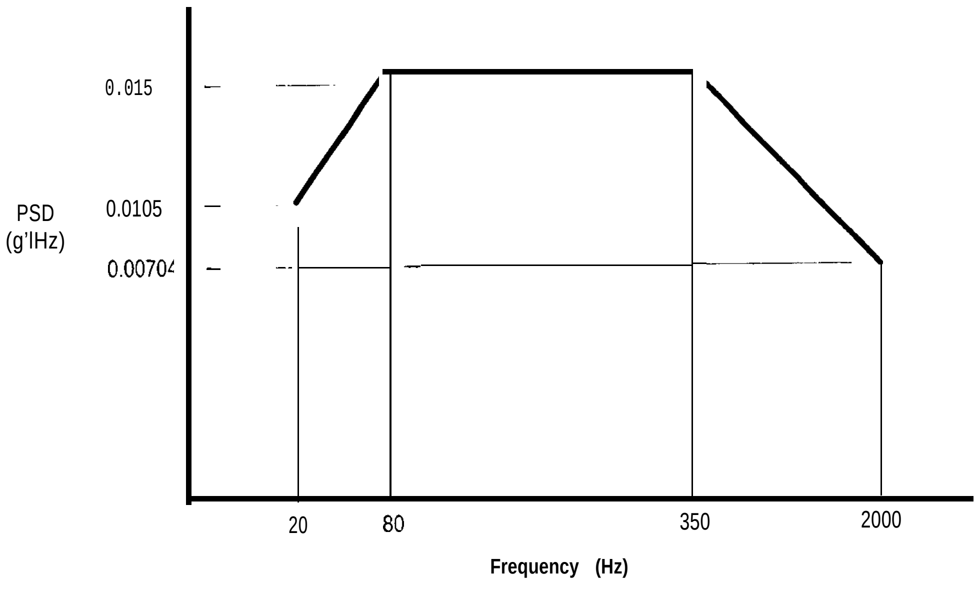


Figure 3-9. ***Product 1 Vibration Profile***

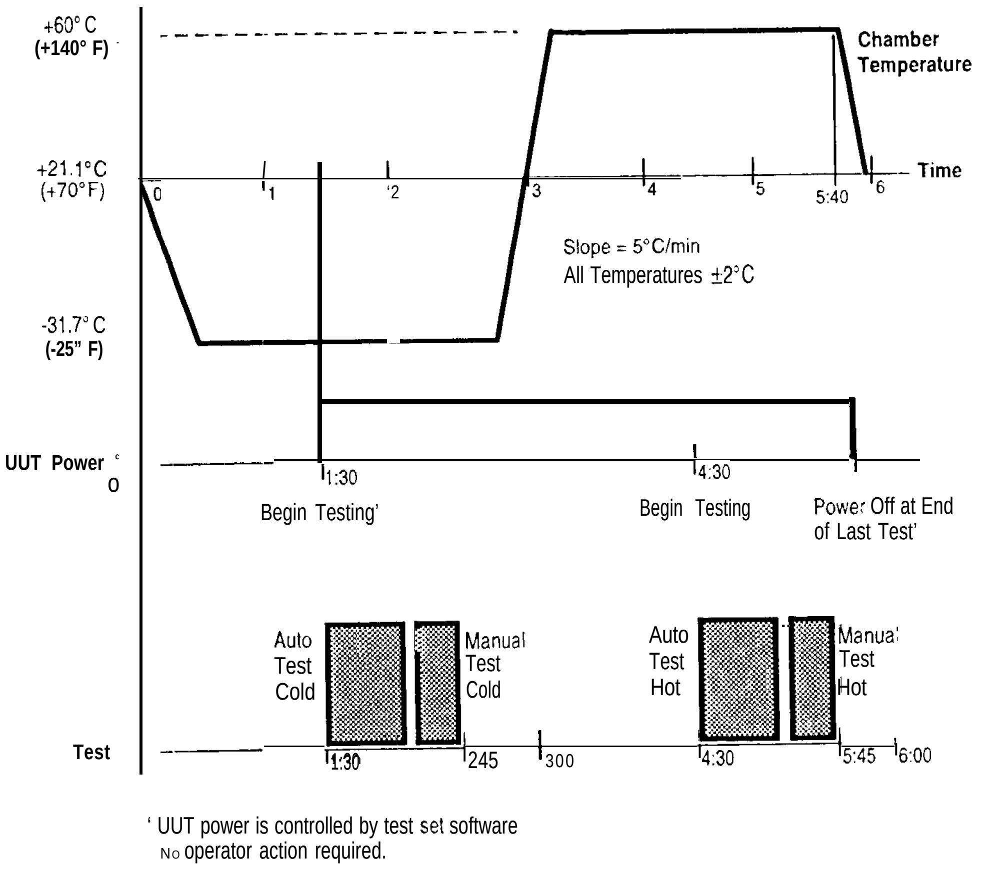


Figure 3-10. Product 1 Temperature Profile

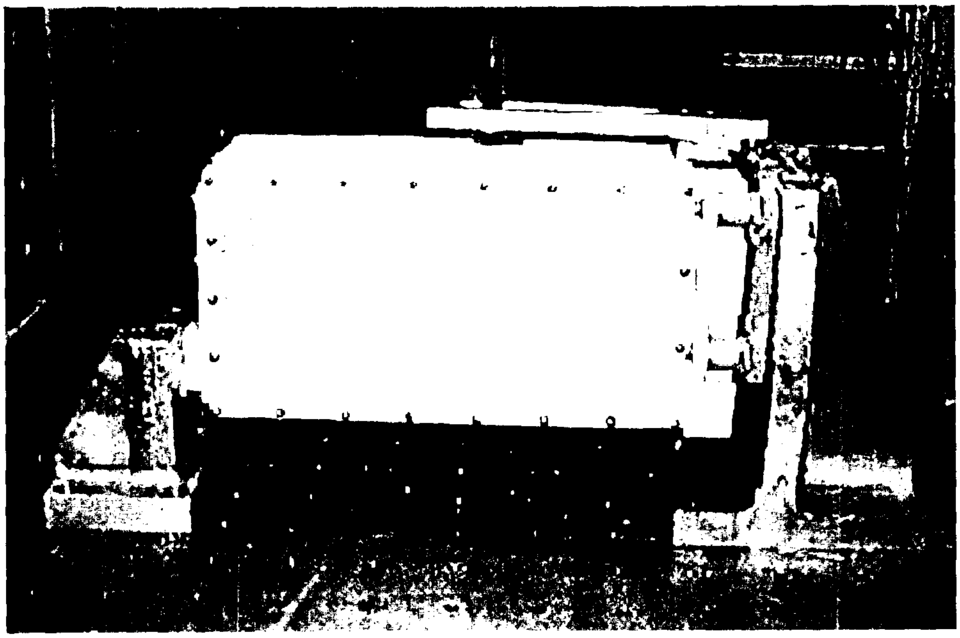


Figure 3-11. Mil-ESS Vibration Fixture

3.3.3 Test Configuration and Equipment

During thermal cycling, an automated computer-driven test set supplied power to each box and automatically tested it. Manual testing at temperature extremes was also performed. Vibration screening was performed without power applied to the product. The vibration table used was an Unholtz Dickie model TA 145 and the thermal chamber used was a Thermotron model F-125 CHV 25-25.

The automated test station contained a host computer that tested performance of the UUT. BIT circuitry in the test sample was also activated. All failures detected set BIT flags identifying the failed unit.

3.3.4 Mil-ESS Results

A total of 20 Product 1 boxes were selected for this baseline evaluation. Of this sample size, four failures occurred, averaging 0.2 failures per box.

3.4 HASS

The HASS procedure used on Product 1 subjected production boxes to a total of four HASS cycles (Figure 3-8). If a failure occurred during a cycle, the cycle was completed, the test sample removed for analysis and repair, and the sample returned to complete the four-cycle requirement. No failure-free cycling was required. Repaired assemblies were retested under the same conditions that surfaced the failure.

3.4.1 Fixtures

The fixture used for HASS was the same as that used for HALT described in Subsection 3.1.2.

3.4.2 Test Configuration and Equipment

The lest configuration and equipment used for HASS were the same as that used for the HALT described in Subsection 3.1.4.

3.4.3 Test Sample Monitoring

Test sample monitoring was the same as that defined for HALT in Subsection 3.1.4.1. Six Product 1 production boxes were subjected to HASS.

3.4.4 HASS Results

Of the six production boxes subjected to HASS, three ran failure-free, A total of four failures occurred on the other three boxes at CCA temperatures of either -55° or +85°C: two during temperature only and two with temperature/ vibration. This equates to 0.7 failures per box. Baseline ESS resulted in 0.2 failures per box for the 20-box sample.

Further analysis revealed that two of these failures at -55°C were design margin related, exceeding customer product specifications by 23°C, and have never failed in the field. The screen was modified to account for this anomaly. Removal of these failures from the analysis puts the failures at two for the six boxes screened or 0.3 failures per box. For this small sample size, it could not be proven statistically that failure percentages differ.

3.5 Cost Analysis

Since an assumption was made that the product yields through the different ESS processes would be similar, the cost analysis became a study about which ESS process cost less to run. A comparison of consumables, floor space, and chamber volume for the chambers and vibration tables used during this evaluation is shown in Table 3-2. A comparison of the relative cost per unit/ box screened between the Mil-ESS baseline process and the HASS process is shown in Table 3-3.

3.6 HALT/HASS Conclusions

The conclusions are based on achieving similar product yields through the Mil-ESS and HASS processes. The Mil-ESS required performing 10 min of random vibration in one axis followed by four thermal cycles, with the last two being failure free. HASS required four thermal/ vibration cycles. The conclusions for Product 1 based on Mil-ESS and HASS testing are:

- Military hardware can be subjected to the accelerated environments of HALT/HASS without damaging product.
- Fixtures are much simpler and less costly for HASS.
- The cycle time for screening product 1 could be reduced by approximately 88% by using HASS.
- HASS, with its accelerated environments, uses a much shorter ESS duration, which allows the throughput of the HALT/HASS chamber to be significantly higher than the Mil-ESS chamber, resulting in a lower unit cost for screened assemblies.
- The percent of cost reduction for HASS is driven by the production volume. Higher production quantities result in much larger cost reductions per unit screened than with Mil-ESS.

Table 3-2. Comparison of Consumables

Item	Baseline	HASS
Electricity per run	481 kW-hr	72 kW-hr
LN_2 per run	N/A	103 gal
Required floor space	150 ft^2	100 ft^2
Chamber volume	64 ft^3	32 ft^3

Table 3-3, Relative ESS Cost Comparison

	Boxes Screened Per Quarter											
	60			120			174			792		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Baseline (3 boxes/run)	xl	X2= 0.95 x 1	x2 = 0.95 x 1	x3	x4 = 0.965 x 3	x4 = 0.965 x 3	x5	x6= 0.973 x 5	x6 = 0.973 x 5	x7	x8 = 0.983 x 7	x8 = 0.983 x 7
HASS (2 boxes/run)	0.8 x 1	0.846 x 2	0.775 x 2	0.69 x 3	0.718 x 4	0.67 x 4	0.644 x 5	0.662 x 6	0,627 x 6	),39 x 7	0.397 x 8	0.39 x 8
Cost Reduction Using HASS (%)	20	15.4	22.5	31	28.2	33	35.6	33.8	37.3	61	60.3	61

Notes: Baseline costs defined as xl - x8

HASS costs defined as a fraction of baseline costs

Case 1: New environmental equipment (Baseline and HASS)

Case 2: Baseline environmental equipment fully depreciated; new HASS environmental equipment

Case 3: Baseline environmental equipment fully depreciated; HASS environmental equipment fully depreciated

4. Technology Evaluation: Electrodynamics Accelerated Life Test/ Accelerated Stress Screen (ED-ACLT/ACSS)

An evaluation was performed comparing the ED-ACLT/ACSS process to the Military Environmental Stress Screening (Mil-ESS) process on Product 2. Product 2, which is manufactured and screened in low quantities, is described more fully in Appendix A. The evaluation involved performing an ED-ACLT on the product, a proof of screen (POS), and running the product through the Mil-ESS and ED-ACSS.

4.1 Electrodynamics ACLT

The following subsections describe how the ED-ACLT process was applied to a Product 2 assembly using temperature, rapid temperature transitions, vibration, and combined temperature/vibration stressing.

4.1.1 Test Procedures

The five tests listed below and discussed in the following subsections were performed during the ED-ACLT:

1. Cold thermal limit determination
2. Hot thermal limit determination
3. Fast thermal cycling limit determination
4. Vibration limit determination
5. Combined environmental exposure

One Product 2 unit was utilized for ED-ACLT. This sample size was based upon the availability of test units for the project.

4.1,1,1 Cold Thermal Limit Determination

The test started by running the unit under test (UUT) diagnostics at room temperature. The temperature was then stepped down to -30°C and held at that temperature for a 10-min minimum. The temperature was then dropped to -50°C and held at that temperature for 10 min minimum. The temperature was then dropped in 10°C increments until the chamber temperature limit was reached. At each temperature increment, the following sequence was performed:

1. The UUT diagnostics were run a minimum of three times with 28 VDC supplied to the UUT.
2. Power to the UUT was turned off, and the supply voltage was raised to 29.5 VDC.
3. Power to the UUT was turned back on, and the UUT diagnostics were run a minimum of three more times.
4. Power to the UUT was turned off. This time, the supply voltage was lowered to 24 VDC.
5. Power to the UUT was turned back on, and the diagnostics were run a minimum of three more times.

This sequence continued for each temperature step until the destruct limit or the limit of the chamber temperature was reached.

4.1.1.2 Hot Thermal Limit Determination

The high-temperature limit test began by running the UUT diagnostics at room temperature. The temperature was then stepped up to 80°C and held at this temperature for a 10-rein minimum. The temperature continued to be stepped up in 10”C increments and held at each temperature for a 10-min minimum. At each temperature increment, the five-step sequence described in Subsection 4.1.1.1 for the cold-temperature limit test was performed for the high-temperature limit test.

This sequence continued for each 10°C step until 160°C was reached. The hot thermal test limit was set at 160”C in order to stay at least 20”C below the liquidus temperature of the eutectic tin-lead solder.

4,1,1.3 Fast Thermal Cycling Limit Determination

The test was started at room temperature, and then the temperature was ramped down to -50°C. The ramp rate was programmed to get to temperature as quickly as the system would allow. The liquid nitrogen (LN_2) boost was used, and the UUT was allowed to dwell at the temperature extreme for 15 min. The temperature was then ramped up to 120"C and the UUT was allowed to dwell at this temperature for 15 min. This procedure was repeated for three thermal cycles:

1. The first cycle was run with a 28-VDC power supply to the UUT. The power was cycled off/on two times during each dwell.
2. The second cycle was run at 29.5 VDC. Power was again cycled off/on two times at each temperature dwell.
3. The third cycle was run at 24 VDC. The UUT power was again cycled off/on two times at each dwell.

After reviewing the thermocouple data for the first cycle, it could be seen that the chamber temperature controller started throttling back at about -35°C and +105°C. This throttling caused the IJUT to not quite reach the program temperature extremes. To help the UUT reach the extremes, the temperature controller was programmed for all future runs to overshoot the desired temperature by 10°C for 12 min prior to the 15-rein dwell. The desired temperature cycle was then set to -60° to +130"C and the test continued for three additional cycles.

When the UUT reached room temperature after the third cycle, the cold setpoint was decreased by 10"C, the hot setpoint was increased by 10"C, and the test continued for three additional cycles. This procedure was repeated through the temperature range of -70° to+ 150°C. (Note: the low-end temperature was limited to -70°C by the 1 i mits of the thermal chamber.) The average ramp rate from cold to hot was 24 °C/min, while the average ramp rate from hot to cold was 16°C/min, as measured at the product.

4.1.1.4 Vibration Limit Determination

The vibration step-stress test began with a 10-rein dwell at 0.01 g^2/Hz input (3.4 G_{rms}, 20 to 2,000 Hz bandwidth) at the vibration table. The vibration supply was increased in the following sequence:

1. To 0.04 g^2/Hz (6.8 G_{rms}) for 10 rein, then
2. To 0.06 g^2/Hz (8.4 G_{rms}) for 10 min, then
3. To 0.08g^2/Hz (9.7 G_{rms}) for 10 rein, and finally
4. To 0.1 g^2/Hz (10.8 G_{rms}) for 30 min.

The UUT diagnostics were run continuously with 28 VDC supplied to the UUT (see Figure 4-1).

4.1.1.5 Combined Environmental Exposure

The UUT was exposed to successively higher thermal stresses in combinat ion with vibration. The initial vibration table input was set at 0.1 g^2/Hz (10.8 G_{rms}). The initial thermal stress temperature range was set at -70° to + 140°C. The temperature dwells at the cold and hot extremes were 27 min. The last 10 min of each temperature dwell included vibration. The rate of temperature transition was set to go as fast as the chamber would allow with the LN_2 boost. The UUT diagnostics were run continuously.

The supply voltage was set at 28 VDC and two thermal cycles were run. The temperature range was then increased from -70° to + 150"C with the same vibration input and sequence. The UUT diagnostics were continuously run again.

The supply voltage was set at 28 VDC and 10 test cycles were completed using the -70° to +150"C temperature range.

4.1.2 Test Configuration and Equipment

During 13 D-ACLT, the Product 2 unit was connected to a test station and supplied with various inputs (power, low level, frequency, communication) and loads. The environmental testing was performed in a Therrnotron model F-32

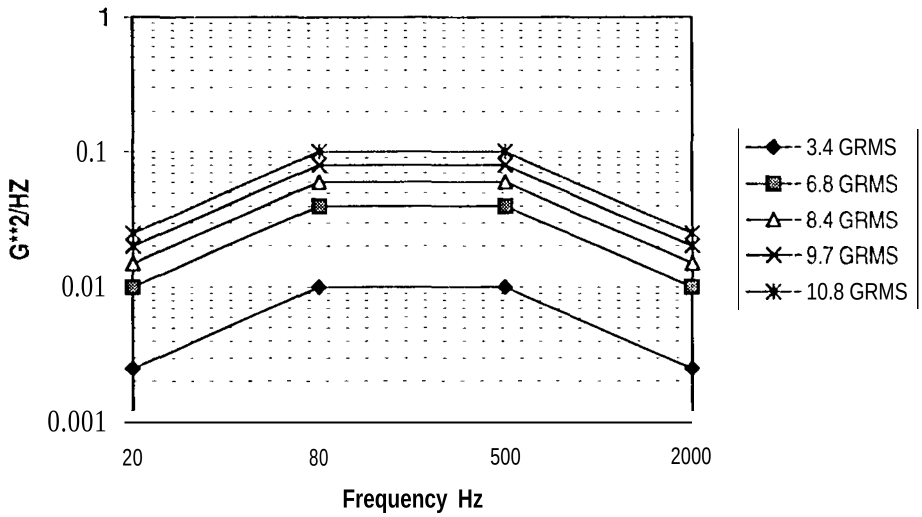


Figure 4-1. Product 2 Vibration Input

thermal chamber with aDS-4001 electrodynamics vibration table. The chamber was retrofitted with an additional heat and LN_2 boost system.

The chamber used open-coil Nichrome heating elements for positive temperature changes and a cascade refrigeration system with two 15-hp compressors for negative temperature changes.

The LN_2 boost system, using a LN_2 Dewar container plumbed with a vacuum tube to the top of the thermal chamber, was used to boost the cooling ramp rates. The chamber incorporated a nozzle that sprayed the LN_2 toward the back of the chamber between the resistance heaters. The chamber air was ported so that the hot or cold air circulated down the sides of the chamber and was recirculated by two ¾-hp propeller-type fans located at the top center of the chamber.

The electrodynamic vibration system included a double-ended gap, low-profile, air-cooled electrodynamic vibration table. The vibration table can provide up to 4,500 pounds force over the frequency range of 20 to 2,000 Hz. The chamber was capable of providing both thermal cycling (-70° to+160°C) and single-axis electrodynamics random vibration (> 10.8 G_{rms} over 20 to 2,000 Hz).

4.1.2.1 Test Sample Monitoring

The UUT was continuously monitored during the ED-ACLT and POS. A test station was used to determine the status of the UUT. Thermocouples and accelerometers were installed on the UUT and on the test chamber. Power on/off cycling and power supply voltage margining were performed as described in Subsection 4.1.1.1. A diagram of the test setup is shown in Figure 4-2.

4.1.2.2 Failure Criteria

The test station contained a host computer that commanded the unit to run test diagnostics and read the results. Eighteen different diagnostic tests were run during each diagnostic cycle. These diagnostics provided coverage for approximately 90% of all failures that occurred. The host computer compared the results to predetermined limits of operation. If the limits were not exceeded, the unit was considered good and the test diagnostics continued to run. This continued until the test was completed or power was manually turned off to the UUT. If a failure occurred during the test, the failure data, including the exceeded limits of operation, was sent to a printer for a hard copy. This data was then used to troubleshoot the failure to the root cause.

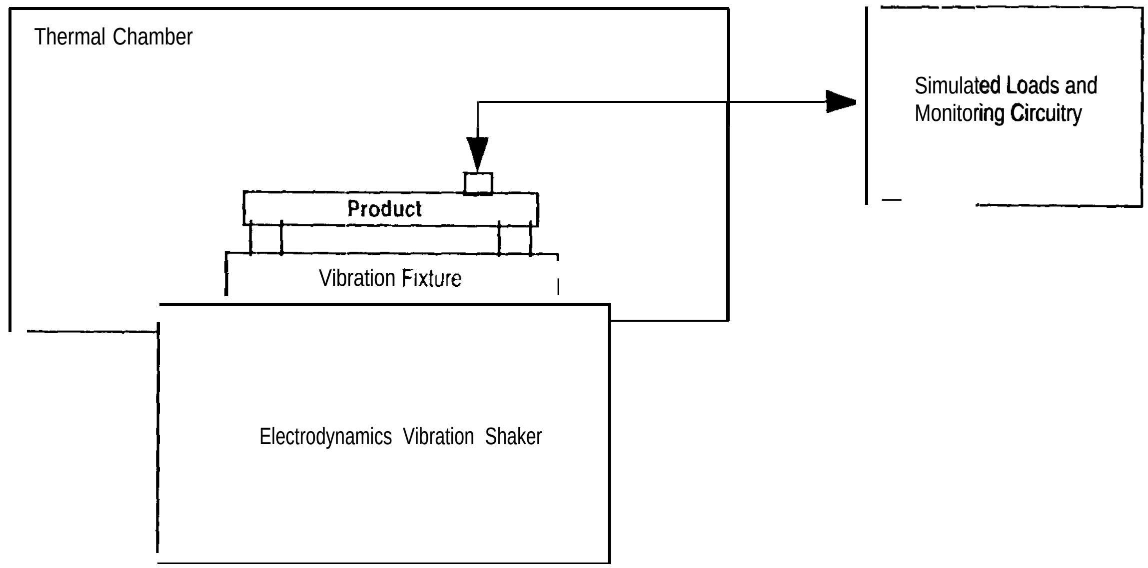


Figure 4-2, ED-ACL T Test Setup

4.1.3 Summary of Results

The failure modes precipitated during the ED-ACLT were as follows:

- The operating temperature limit for the unit was found to be 146°C, at which point the UUT failed an analog-to-digital (A/D) circuit range check during the hot temperature operating limit test. This failure was caused by a pressure sensor circuit going slightly out of its tolerance range due to the hot temperature environment. When the temperature was dropped, the circuit went back into range and the unit continued to operate with its set tolerance limits.
- A failure was precipitated in a through-hole-mounted ceramic capacitor. Two leads were broken during the -70° to+ 140°C combined environment test.
- Two other failures were precipitated. One was a broken 28-VDC wire at an electromagnetic interference (EMI) filter (which connects to the output side of the filter); and the second was a Teflon® capacitor that exhibited an open internal to the component. Both occurred during the -70° to + 150°C combined environment test.

All three of the precipitated failures were determined to be related to the high vibration levels associated with the test environment,

4.2 Proof of Screen

POS was performed on Product 2 to determine if the proposed ED-ACSS screen consumed a significant portion of the product's useful life.

4.2.1 Test Procedures

The POS was developed by analyzing the data obtained from the ED-ACLT. The POS profile consisted of thermal cycling from -60° to + 120°C with programmed 27-min cold and hot temperature dwells and ramping the thermal chamber as fast as it would go. These profiles were set based upon the high and low temperature limit determination tests.

The thermal cycling was combined with 0.06 g^2/Hz random vibration (8.4 G_{rms}, 20 to 2,000 Hz bandwidth) for 5 min at both the hot and cold temperature dwells during every third thermal cycle for the first 100 thermal cycles. After 100 thermal cycles, the vibration was applied in the same manner as for the POS profile described above, except that the vibration was applied for 5 min at each hot and cold temperature dwell instead of at every third thermal cycle. The UUT test diagnostics were run continuously and the supply voltage was set at 28 VDC.

4,2,1,1 Sample Size

One Product 2 unit was used for the POS. This sample size was based upon the availability of test unit for the project.

4.2.1,2 Test Configuration and Equipment

The POS test configuration and equipment were the same as described in Subsection 4.1.2.

4,2.1.3 Test Sample Monitoring

The test sample was monitored in the same manner as described in Subsection 4.1.2.1.

4.2.1.4 Failure Criteria

The proposed screen was considered to be usable if the UUT exhibited no wear-out failures for the first 100 cycles of the environment described above. This number of cycles was calculated to represent less than 5% of the product's useful life.

4.2.2 Results

The test unit was exposed to a total of 150 thermal cycles. The total vibration exposure. was in excess of 13.8 hr, with half at the cold temperature and half at the hot. A sample of the thermocouple data collected is shown in Figure 4-3.

One UUT failure was precipitated during the 128th thermal cycle, 4 to 5 min into the vibration portion of the hot-temperature dwell. The failure was in the A/D circuit. It was determined that the A/D failure was caused by the failure of a Teflon capacitor. The capacitor exhibited an open internal to the component, Radiography on the part confirmed that the internal capacitor had broken away from the leads. This failure was of the same type that occurred during the ED-ACLT.

Following the POS, the Product 2 test item was nondestructively disassembled to the subassembly level and visually examined for any evidence of internal or external deterioration. None was detected.

Based upon the POS, a trial lot of production Product 2 units will be subjected to the ED-ACSS. The ED-ACSS profile will consist of five thermal cycles from -60° to+ 120°C with 8.4 G_{rms} vibration input to the UUT for 5 min during the hot and cold dwells of the second and fourth thermal cycles. By performing the screen on a trial basis, the screening effectiveness of the units subjected to the ED-ACSS environment can be compared to the current production sequential thermal cycle followed by vibration environmental stress screen.

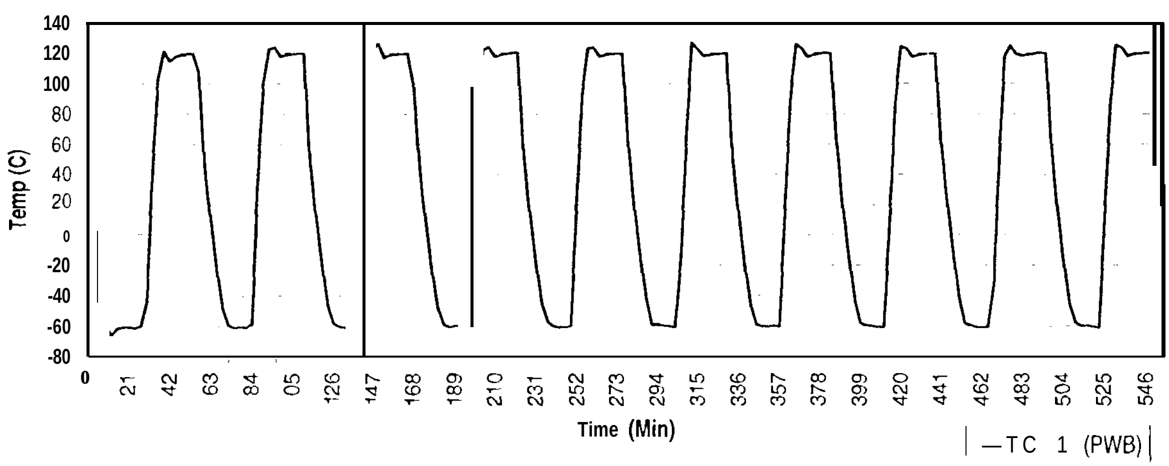


Figure 4-3, Proof of Screen Thermocouple Response Data (Cycles 23-32)

4.3 Mil-ESS

4.3.1 Test Procedures

The process used to manufacture and test Product 2 for the Mil-ESS evaluation involved: manufacturing the printed circuit card assemblies (CCAs) and running them through an electrical test; and then assembling the system and running it through electrical, Mil-ESS, and acceptance testing (refer to Figure 4-4). The Mil-ESS process included 10 thermal cycles from -55° to +85°C followed by 10 min of random vibration at 0.01 g^2/Hz in the plane perpendicular to the printed circuit card assembly (see Figures 4-5 and 4-6).

4.3.2 Sample Size

Mil-ESS test data was collected on 34 units. This sample size was selected based upon the product availability during the project time frame.

4.3.3 Test Configuration and Equipment

During the baseline ESS process, Product 2 was connected to a test station and supplied with various inputs (power, frequency, and communication) and loads. The temperature cycling was performed in an Envirotronics thermal chamber, and the vibration was performed on an Unholtz-Dickie Corporation 560 model electrodynamics vibration table. The temperature chamber used open-coil, electric-resistive heaters for positive temperature changes and a cascade refrigeration system with two 15-hp compressors for negative temperature changes.

4.3.4 Data Acquisition

The Product 2 test station contained a host computer that commanded the unit to run test diagnostics and read the results. Eighteen different diagnostic tests were run during each diagnostic cycle. These diagnostics constituted coverage for approximately 90% of the potential component failures on the CCAs. The host computer compared the results to predetermined limits of operation. If the limits were not exceeded, the unit was passed and the test diagnostics continued to run. This continued until the test was completed or power was manually turned off to the UUT. If a failure occurred during the test, the failure data, including the exceeded limits of operation, was sent to a printer for a hard copy. This data was then used to troubleshoot the failure to the root cause.

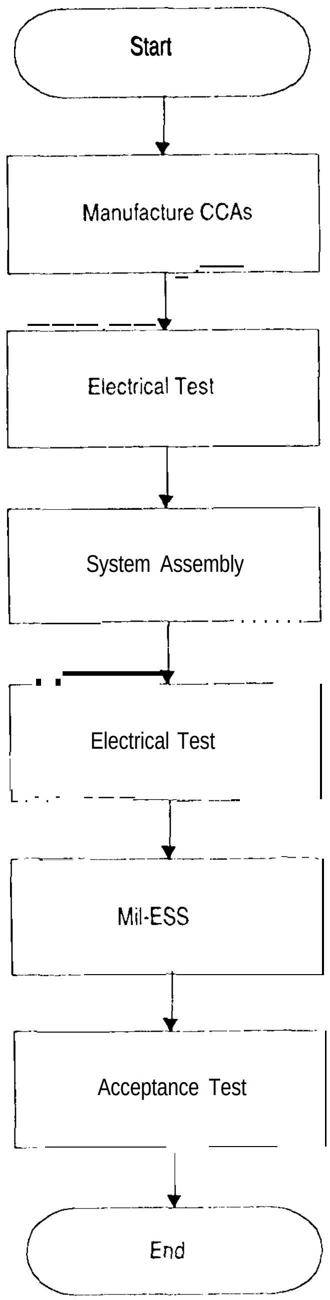


Figure 4-4. Product 2 Mil-ESS Manufacturing Flow Diagram

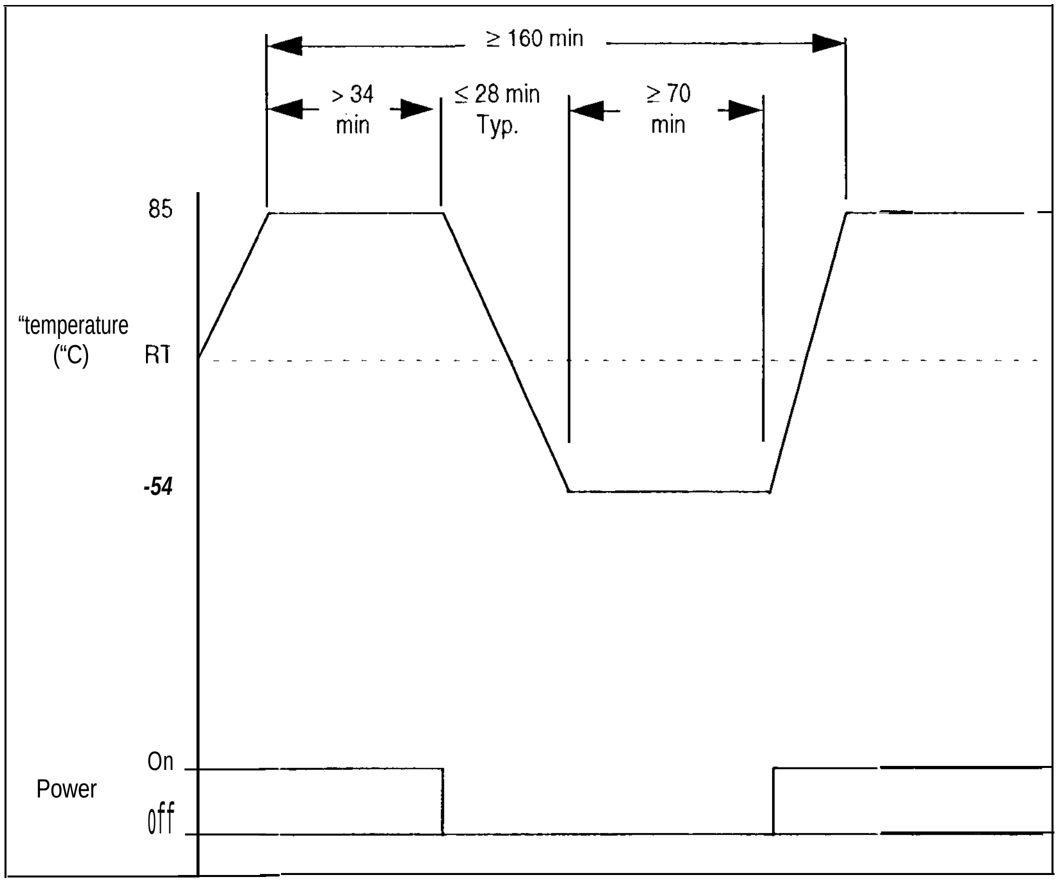


Figure **4-5.** ***Thermal Cycle Profile***

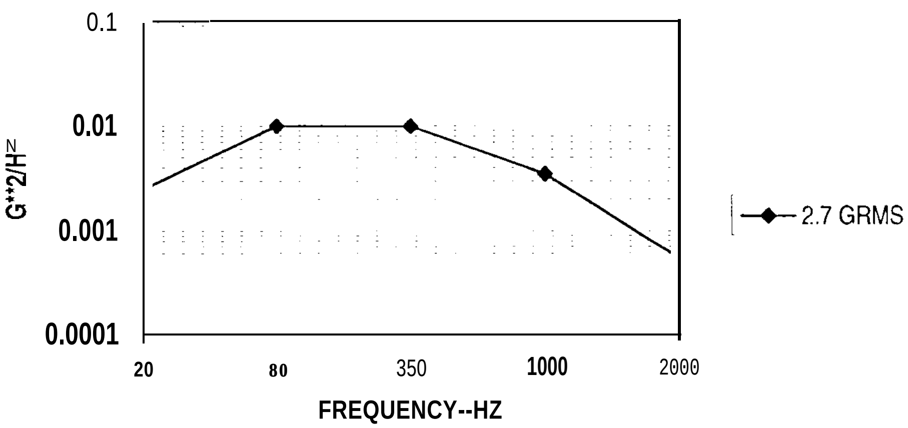


Figure 4-6. ***Vibration Screen Profile***

4.4 Electrodynamics ACSS

An ED-ACSS is scheduled to compare the effectiveness of running ED-ACSS versus the baseline ESS process. As of this writing, the trial has not been completed.

4.4.1 Test Procedures

The manufacturing process used on Product 2 in the ED-ACSS evaluation will be the same as for the Mil-ESS evaluation (see Subsection 4.3 and Figure 4-7). The ED-ACSS used on Product 2 will include five thermal cycles from -60° to + 120"C with 0.06 g^2Hz vibration input to the product (see Figure 4-8). The Mil-ESS to be performed after the ED-ACSS will be used to determine if any defects escaped the ED-ACSS process.

A total of 20 Product 2 units will be subjected to ED-ACSS.

4.4.2 Test Configuration and Equipment

The test configuration and equipment used for the FD-ACSS will be the same as for ED-ACLT (see Subsection 4. 1.2).

4.4,3 Data Acquisition

The same Product 2 data acquisition procedure will be used for the ED-ACSS as for the Mil-ESS (see Subsection 4.3.4).

4.4.4 Data and Failure Analysis Results

Yields of Mil-ESS temperature cycling are shown in Table 4-1.

Table 4-1. Product 2 Mil-ESS Yield

Statistic (including No Defect Found)	Mil-ESS
Number of Cards Screened	34
Number of Cards Failed	9
Yield	73.5%

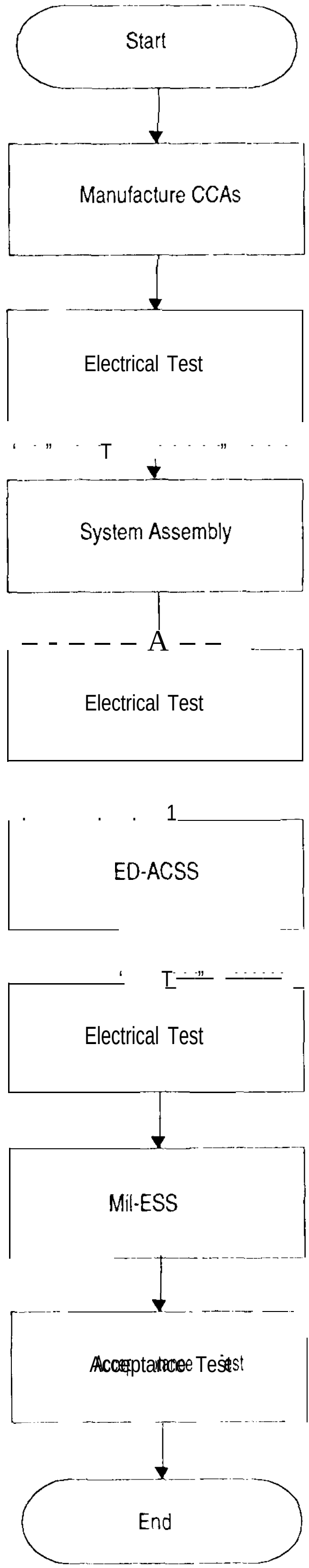


Figure 4-7. Product 2 ED-ACSS Manufacturing Flow Diagram

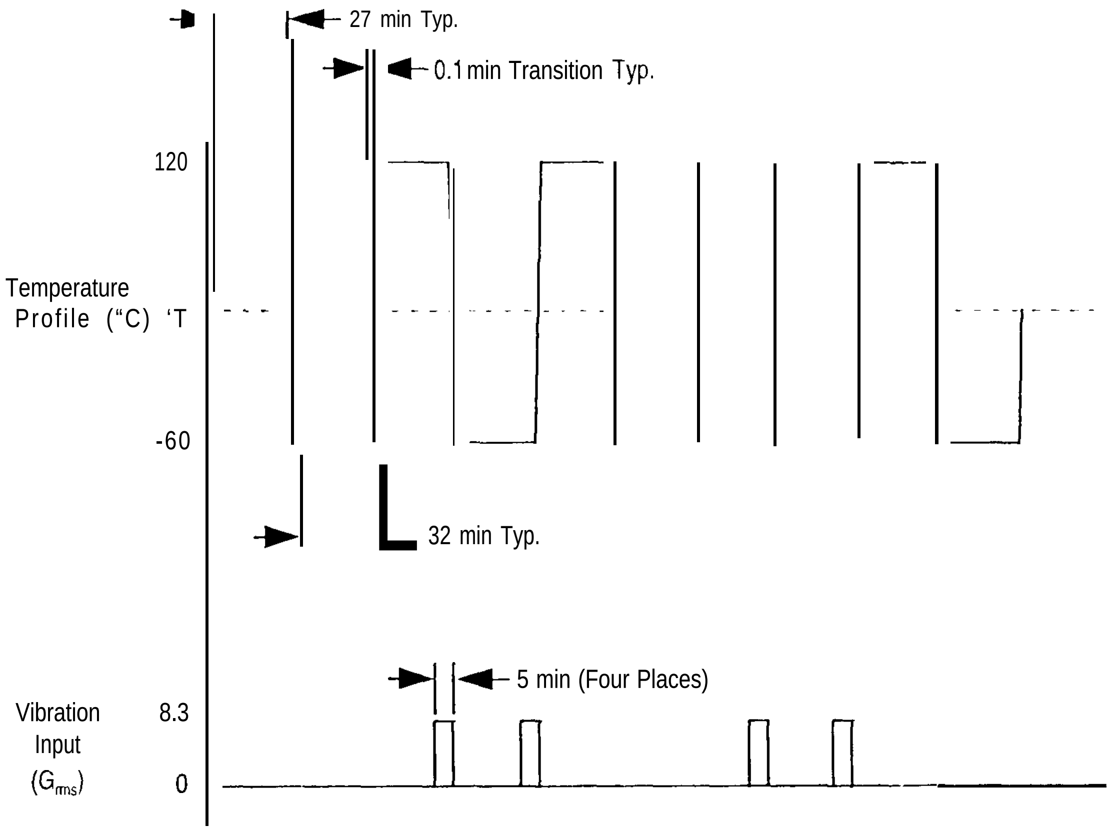


Figure** 4-8. **Product 2 ED-ACSS Profile

The failure analysis identified card and component failure modes. The failure symptoms were analyzed prior to the debug process by reviewing the failure printout from the test station. The product CCA was then disassembled from its housing and electrically tested. The debug process involved isolating the failure to a given circuit. The individual circuit was then troubleshoot manually to identify one or more suspect components. A visual inspection was then performed, followed by additional electrical testing to identify the item that failed. A subsequent electronic component failure analysis was performed, when applicable.

The test yield from the temperature cycling portion of the Mil-ESS was 73.5% (nine failures), while the test yield from the vibration portion of the Mil-ESS was 10070 (O failures). Subsequent in-process electronic testing after ESS but prior to product shipment revealed a yield of 92% (three failures). These three failures appeared to have been precipitated during the vibration portion of the screen, but were not able to be detected, The final acceptance test, performed at room temperature and using tighter circuit tolerances, was able to detect these failures. By increasing the vibration stress, the environmental stress screen may be able to detect these escapes.

Figure 4-9 shows a Pareto chart of the failures that occurred in Mil-ESS.

A Product 2 failure summary for the Mil-ESS process is given in Table 4-2.

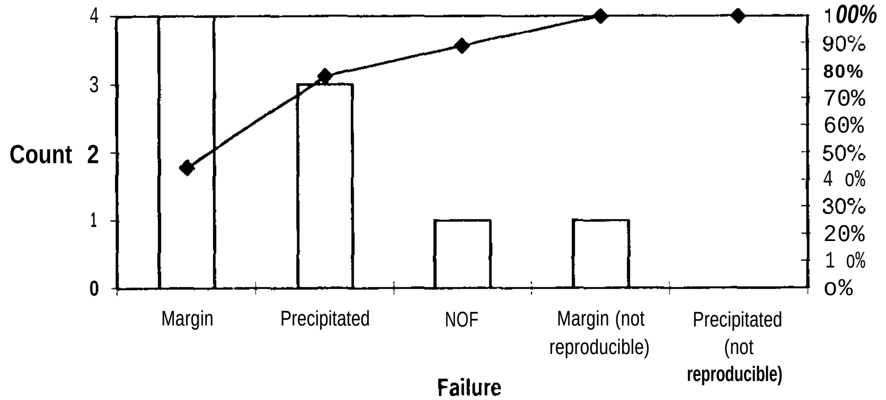


*Figure 4-9, **Product 2 Pareto Chart of Mil-ESS Failures***

Table 4-2. Product 2 Failure Summary for Mil-ESS

Failure	% of Failures	% of Total CCAs Tested
Margin	44.5	11.8
Precipitated	33.3	8.8
NDF	22.2	6.9

Table 4-3. Product 2 Comparison of Consumables and Floor Space

Item	Mil-ESS	ED-ACSS	HASS
Electricity/run (kW-hr)	651	182	90
LN_2/run (gal)	0	52	147
Required floor space (ft^2)	418	343	196

4.5 Cost Analysis

The costs per unit to perform the baseline Mil-ESS, the ED-ACSS alternative, and the HASS alternative were compared for Product 2 using the cost model developed. The following assumptions and parameters were used in the model for Product 2:

- Since product was not run on all of the different screens, an analysis was performed to determine if the yields would be similar. Vibration input levels were adjusted for ED-ACSS and HASS to provide responses at the circuit card assembly natural frequency similar to the Mil-ESS vibration responses. Based upon these types of analyses, it appeared likely that the yields will be similar.

- The consumables, floor space, and chamber volume needed for each screen are given in Table 4-3.

- Since the product yields through the different ESS processes were assumed to be similar, the cost analysis became a study about which ESS process cost less to run.

- The cost model was run for three cases (1, 2, and 3):

  - Case 1: New environmental and test equipment purchased
  - Case 2: Mil-ESS equipment fully depreciated; new ED-ACSS or HASS equipment purchased
  - Case 3: All equipment fully depreciated.

The product was grouped into three different quantities (A, B, and C). The three groups of product were then run for each case through the screen per quarter:

- Qty A: 60 units tested/quarter
- Qty B: 150 units tested/quarter

– Qty C: Maximum quantity of product that could be tested on the equipment with the screen identified (150 units for the Mil-ESS screen and 465 units for the ED-ACSS and HASS).

The results given in Table 4-4 show that no single screen was best for all cases.

However, when the equipment was used to capacity, both ED-ACSS and HASS provided a lower-cost process than the currently used Mil-ESS process.

4.6 Conclusions

The following conclusions can be drawn from the Mil-ESS and the ED-ACLT/ACSS testing on Product 2:

- The ESS duration could be reduced by 78% by using ED-ACSS instead of Mil-ESS.
- The use of Dewar containers for supplying LN_2 for the ED-ACSS is not recommended because of the frequency of changeout.

The following conclusions can be drawn from performing the cost analysis on Product 2:

- For Case 1–Quantity A, equivalent low-throughput volumes, all three screens had a similar cost/product screen.
- When using the maximum throughput of the chambers and new equipment is purchased, both the ED-ACSS and HASS processes provide a lower-cost alternative to the Mil-ESS process, with the ED-ACSS process having a slightly lower cost to perform than HASS. This lower cost was primarily from the increased throughput of the ED-ACSS and HASS equipment over that of the Mil-ESS equipment,
- When equipment costs are not included in the analysis (i.e., they are fully depreciated), the ED-ACSS and HASS processes provide lower-cost alternatives. This lower cost was primarily from the reduced run cycle time of ED-ACSS and HASS. The shorter run cycle time reduced the amount of electricity and LN_2 consumed.

Table 4-4. Product 2 Cost Model Analysis Results

Case No.	Capital Equipment	Qty Group	Quantity Units/Quarter	of Mil-ESS*	ED-ACSS*	HASS*	Lowest Cost
1	All new equipment	A	*60*	X_{1A}	1.03 X_{1A}	0.99 X_{1A}	HASS
1		B	150	X_{1B} , (X_{1B} = 0.54 xl,)	1.04 X_{1B}	1.05 X_{1B}	Mil-ESS
1		c	Max. capacity	X_{1C} , (X_{1C} = 0.54 X_{1A})	0.65 X_{1C}	0.70 X_{1C}	ED-ACSS
2	New Equipment – ED-ACSS and HASS only	A	60	X_{2A} , (X_{2A} = 0.53 X_{1A})	1.91 X_{2A}	1.83 X_{2A}	Mil-ESS
2		B	150	X_{2B} , (X_{2B} = 0.36 Xl,)	1.57 X^*_B	1.58 X_{2B}	Mil-ESS
2		c	Max. capacity	X_{2C} , (X_{2C} = 0.36 X_{1A})	0.99 X_{2C}	1.06 X_{2C}	ED-ACSS
3	All equipment fully depreciated	A	60	X_{3A} , (X_{3A} = 0.53 xl,)	0.94 X_{3A}	0.83 X_{3A}	HASS
3		B	150	X_{3B} , (X_{3B} = 0.36 X_{1A})	0.99 X_{3B}	0.98 X_{3B}	HASS
3		c	Max, capacity	X_{3C} , (X_{3C} = 0.36 X_{1A})	0.79 X_{3C}	0.86 X_{3C}	ED-ACSS

* Where X_{1A} through X_{3C} represent the cost per unit to run the Mil-ESS for the case shown.

5. Technology Evaluation: Liquid Environmental Stress Screen (LESS)

As part of the ESS 2000 Project, a comparison between LESS and Highly Accelerated Stress Screen (HASS) was performed. The objective of this comparison was to evaluate the relative merits (capabilities and costs) of the two technologies. Two phases of work contributed to this portion of the investigation.

The first phase, safety of screen, involved a comprehensive examination of the Liquid Environmental Stress Test (LEST) machine and its corresponding LESS process for possible deleterious effects upon well-manufactured circuit card assemblies (CCAs). To maximize technology diversity, Products 1, 2, and 3 were evaluated in this portion of the testing. Details are given in Subsection 5.1.

The second phase involved subjecting a large quantity of product to both LESS and HASS to evaluate and compare the two technologies. Because of the large sample sizes required, only Product 3 (further described in Appendix A) was involved with this portion of the analysis. Details are given in Subsection 5.2.

Traditionally, 10 thermal cycles have been used in production LESS. Although LESS may be run with fewer cycles and consequently shorter test duration, 10 cycles was adopted as the Environmental Stress Screening (ESS) duration for all liquid production screening performed during Ibis project.

5.1 Safety of Screen

The safety of screen was used to verify that LESS does not damage product. To gain this confidence, test samples were subjected to a minimum of 100 LESS cycles (shown in Figure 5-1). This screen involved initial quantification of the operating performance of the product, exposure of the product to varying degrees of liquid thermal shock, subsequent testing of the product, and a reevaluation of the product's operating performance.

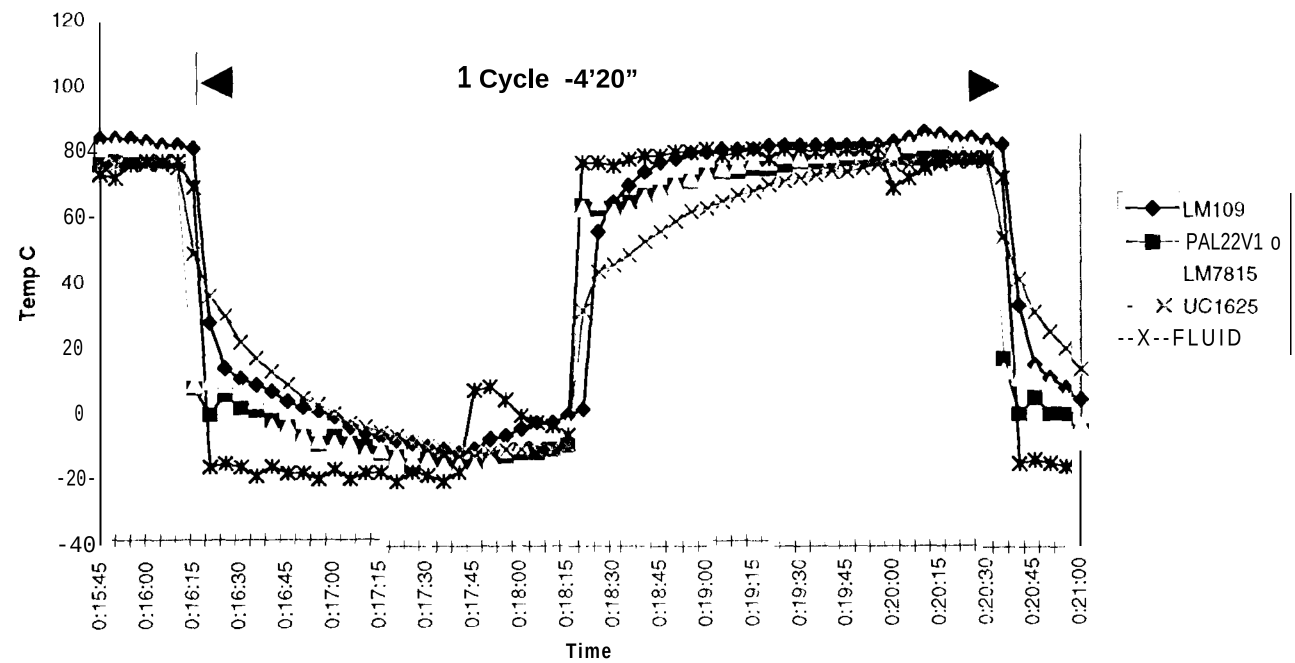


Figure 5-1. Generic Safety of Screen – LEST Temperature Profile

Since an objective of the LESS safety of screen evaluation was to maximize technology diversity through involvement of multiple products, no test procedures, sample sizes, and test configurations were alike. Included in the subsequent safety of screen sections are brief descriptions associated with each product.

5.1.1 Test Procedures

Product 1 test procedure involved initial power-on tests at ambient temperature to verify proper operation. The LEST machine was then cycled up to 100 cycles. The product was nonoperational during some. of the cycles.

In the case of Product 2, two assemblies were tested in the LEST machine. One assembly was exposed to 50 thermal cycles, and the other exposed to 300 thermal cycles. The assemblies were normally powered during the testing, however, power to the unit was cycled off, then back on during every second or third cold soak.

Product 3 was exposed to a range of LEST cycle counts of 10, 50, 100, and 200. To avoid any possible deleterious effects by outside sources, a control group was included, which did not experience thermal cycling.

Although the actual number of LEST cycles varied between products 1, 2, and 3, common elements exist. All cards were subjected to the following testing process:

- Initiate test at room temperature
- Hot fill/dwell at +80°C (~90-sec duration)
- Drain hot fluid (~30-sec duration)
- Cold fill/dwell at -20°C (~90-sec duration)
- Drain cold fluid (-46-see duration)
- Repeat sequence for each additional cycle.

A graph of temperature versus time during a LEST safety of screen cycle is shown in Figure 5-1. Although the temperature profile is based upon product 1, it is consistent with those seen on Products 2 and 3. This consistency is due to the properties of the fluid (see Appendix B for details).

5.1.1.1 Sample Size

The sample size of the liquid thermal shock evaluation was limited to card availability and, as a result, did not have statistical significance. For product 1, a total of seven fully operational CCAs and three printed wiring boards were subjected to liquid thermal shock. For Product 2, two production CCAS were tested. Product 3 used 28 CCAs in its tests; 24 witnessed some quantity of LESS cycling while 4 served as the control group. (A list of the relevant board technologies tested is in Appendix A.)

5.1.1.2 Test Configuration, Equipment, and Fixtures

Product 1 was connected to a system hot mock-up with extender cables. A test set, which was placed next to the chamber with extender cables long enough to connect to the product, was used to apply power and control the system. For Product 2, the assembly was removed from its aluminum housing and connected to a test station supplying various inputs (power, frequency, communication) and loads. Product 3 was mounted in a specially designed fixture and connected to an exterior-mounted power supply.

5.1.1.3 Test Sample Monitoring

Product 1 performance was verified with the test set pass/fail indicators and with visual monitoring of the video. Product 2 was normally powered during testing; however, power to the unit was cycled off, then on during every second or third cold soak. The unit under test (UUT) was continuously monitored during the safety of screen, except during power cycling. For Product 3, no monitoring was performed during the safety of screen. The cards were, however, powered with their standard 5.1 VDC.

5.1.1.4 Failure Criteria

Correct operation of Product 1 in a system configuration was determined by both the system and the test set built-in test (BIT) functions and visual monitoring. For product 2, 18 different diagnostic tests were run during each diagnostic cycle. The results were compared by the host computer to predetermined limits of operation. If the limits were not exceeded, the unit was considered good and the test diagnostics continued to run; otherwise, this data was then used to troubleshoot the failure to the root cause. For Product 3, the operation of the cards was characterized in a full factorial temperature and voltage test prior to and after the safety of screen. Any significant changes in the operational performance of the cards resulting from the safety of screen were detected by changes in the full factorial test outputs.

5.1.2 Safety of Screen LESS Results

For Products 1 and 3, no failures occurred during the LESS cycling. During subsequent testing, one failure of Product 1 occurred at the 960 hr of a 1,000-hr life test, This failure was the result of moisture absorption by resistors after prolonged exposure to the 85°C/85% relative humidity environment and not attributed to the LEST machine. Product 3 suffered no performance degradation due to LESS.

Product 2 experienced failure during the safety of screen because of a partially enclosed sensor. This failure was the result of an incompatibility with the liquid thermal shock fluid. Products that could retain fluid may not be compatible with the LESS process.

An analysis of the LEST safety of screen product performance data indicates that no product experienced any measurable adverse effects due thermal cycling up to 300 cycles. Visual inspection indicated no damage to the boards as a result of the testing; however, certain components did temporarily retain the LESS working fluid. This did not have an adverse long-term impact on the product.

5.2 LESS Versus HASS Evaluation

Product 3 used for this portion of the evaluation was an existing product with an existing HASS process. Consequently, the project team found no benefit in repeating the Highly Accelerated Life Test (HALT) and accepted the existing HASS process.

To obtain unbiased data, baseline HASS and LESS data were collected simultaneously. Data from Product 3 was used for this portion of the analysis due to its high-volume availability.

5.2.1 Test Procedures

The processes for performing HASS (the baseline process for Product 3) and LESS were very similar, as illustrated in Figure 5-2.

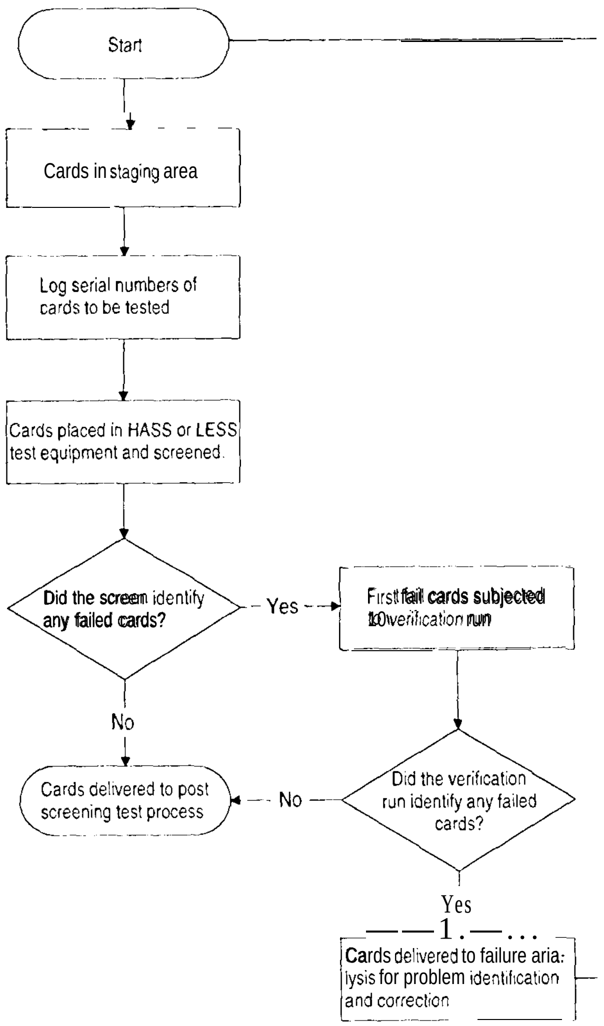


***Figure 5-2. Product 3 HASS and* LESS Manufacturing *Flow* Diagram**

In particular, the methods of logging and preparing cards for screening did not differ between the processes. Although the process by which the cards are prepared for screening was very similar for HASS and LESS, the actual screen profiles differed significantly, as shown in Figures 5-3 and 5-4.

5.2.1.1 Sample Size

A sample size of over 1,500 CCAS was selected to allow a statistically significant analysis to be performed. During the test, 1,555 cards were subjected to LESS and 3,661 cards to HASS.

5.2.1.2 Test Configuration, Equipment; and Fixtures

The HASS chamber used for this investigation was a QualMark OVS-4. It contained a 16-ft^2 vibration table and used liquid nitrogen (LN2) cooling. The proprietary Product 3 vibration control system was used in conjunction with a JC Systems FastTRAC 620 temperature controller.

Four Hewlett Packard (HP) 6633A system power supplies provided power to the product. The power supplies were controlled through an HP IB bus with an HP 7 15/33 Apollo Workstation. Custom software based upon the HP Vee programming platform controlled the operation of the chamber and the testing of the cards.

The LEST chamber, model EST3 (2)-10 OWC, used for this investigation was a Lucent Technologies system. It was manufactured by ESPEC Corporation for Bell Laboratories. (Refer to Subsection 2.4.1.1 for LESS equipment details.)

The unique environments of the HASS and LESS environments required the development and manufacture of unique card fixtures. For HASS, the fixture was designed to contain 23 CCAs. Conditioned air was directed through the top and exited at the base of the fixture. Vibration was transmitted from the table to the product through the fixture.

The LEST machine contained two test chambers, each holding one test fixture. The test fixture design accommodated a maximum number of cards while allowing easy access. Each fixture contained 10 cards, resulting in a maximum throughput of 20 cards per run.

5.2.1.3 Test Sample Monitoring

The CCAS were functionally tested once per test step during the screen. During functional testing, 10 tests were performed, resulting in approximately 90% coverage of the board components.

5.2.2 Data and Failure Analysis Results

To ensure the accuracy of the data interpretation and to allow for proper comparisons between LESS and HASS, significant data analysis was required. Data analysis manifested itself in data reduction and failure categorization.

Data reduction was performed to compare the LESS and the HASS data. Factors such as card randomization, holiday testing shutdowns, and process errors were taken into account.

Failure categorization constituted the second phase of the data analysis. (Refer to Section 2, Table 2-2, for terms and definitions.)

The cards rejected during LESS and HASS screening followed the standard company manufacturing procedures for rejected material. These procedures included database entries for all cards that failed and were sent to failure analysis in order to track the card and record failure information. The failure symptoms (failure type, temperature, and voltage) of each card were analyzed before the failure analysis process began.

The failure analysis method for the card depended upon the results of the failure symptoms analysis. The failure analysis process always involved an initial visual inspection of the failed card, followed by specific test techniques appropriate for the conditions in which the failure occurred.

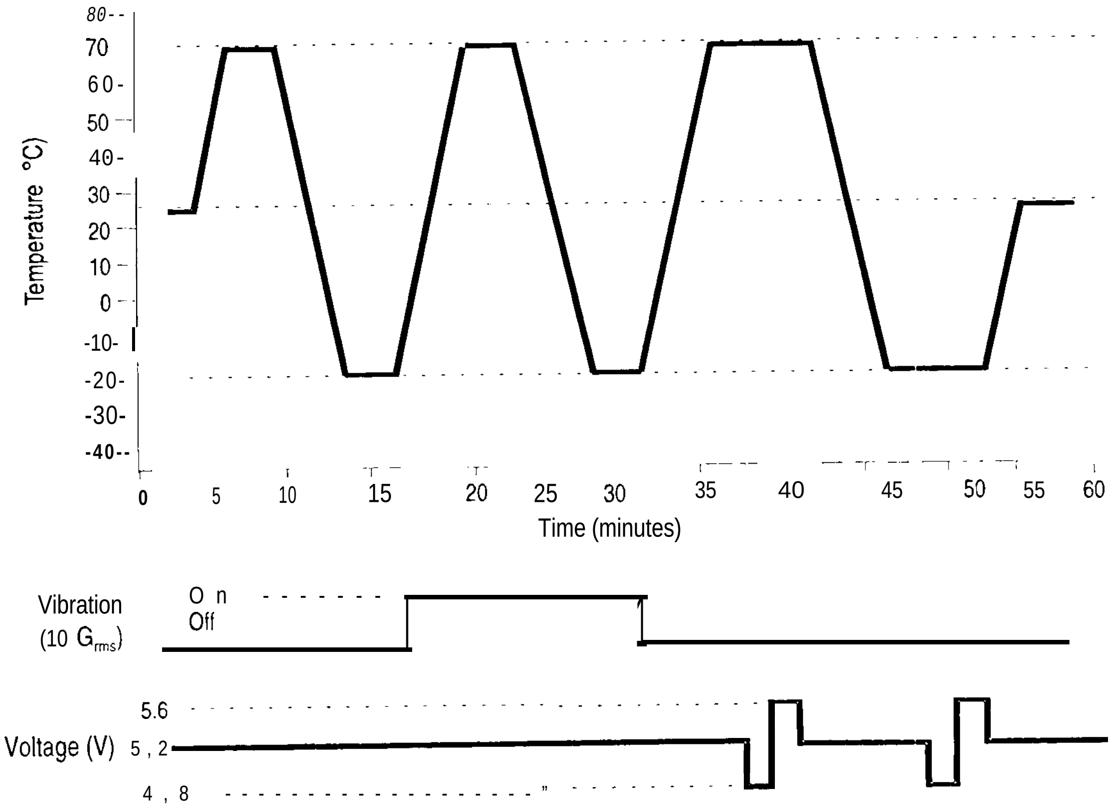


Figure 5-3. HASS Profile

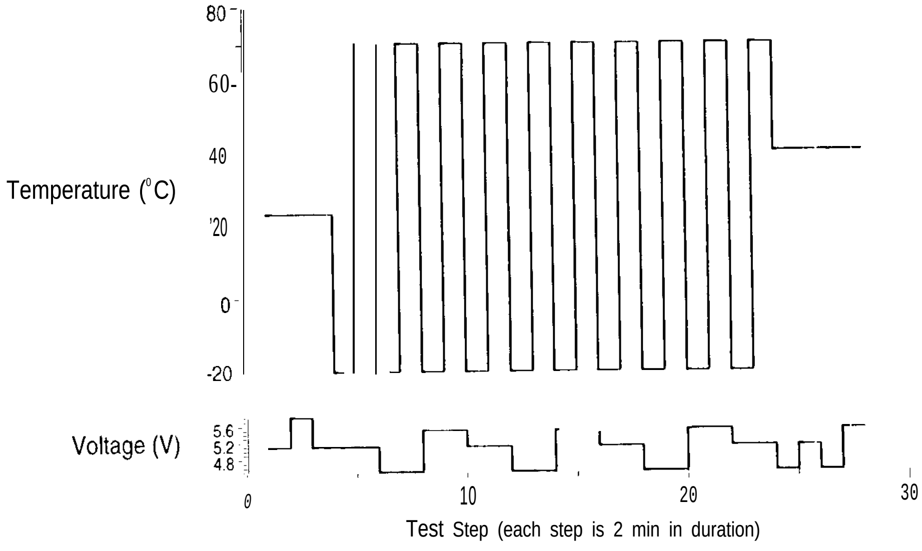


Figure 5-4. LESS Profile

The failure analysis team was occasionally unable to duplicate the HASS failure using the tools at its disposal. Consequently, the failed cards were re-subjected to the HASS process. (In the case of LESS failures, the cards were also subjected to a subsequent HASS process). If the card passed the "failure analysis HASS," it was set aside for more detailed failure analysis.

All actions to determine failure mode and root cause were recorded in a failure analysis spreadsheet and used in subsequent analyses. The data was then downloaded to the ESS 2000 database.

5.3 Summary of Results

Data from the Value Added Screening Effectiveness (VASE) matrix process was used to generate four types of results:

1. Table 5-1 is the VASE matrix for the HASS process.
2. Table 5-2 is the VASE matrix for the LESS process.
3. Table 5-3 is the top-level VASE matrix, which presents confidence level estimates of the detection effectiveness of HASS as compared to LESS for the tall-pole failure modes.
4. Table 5-4 is a VASE matrix that presents the confidence level estimates for HASS versus LESS for each of the failure manifestation categories. The data collected for statistical comparisons of the relative effectiveness between HASS and LESS for Product 3 was analyzed for:
   - Overall yield (Table 5-5)
   - The way the failures manifest themselves (Table 5-6)
   - The specific failure modes or mechanisms detected by each screen (Table 5-7)
   - The particular stresses that were determined responsible for surfacing each defect in HASS and LESS (Figures 5-5 and 5-6).

At the highest level of analysis, the two scl-tens exhibited similar yields (percent passing). Although the yields at the highest level of the HASS and LESS processes were statistically identical, the breakdown of the failures that make up these yields were not, as described below:

- **Dead on Arrival (DOA): DOAs accounted for 0.9% and 0.65% of the total number of** CCAs tested in LESS and HASS, respectively. The higher DOA count in LESS was attributed to the additional handling, packaging, and transportation required by the Product 3 process prior to screening at the LESS facility.
- **Margin Failures: The evaluation team could not reject the null hypothesis** that HASS is equal to or more effective than LESS testing for failures that manifest as margin "failures" to the 96% confidence level.
- **Precipitated Failures:** The evaluation team could not reject the null hypothesis that HASS is equal to or more effective than LESS testing for failures that manifest as precipitated "failures" to the 63% confidence level.
- **No Defect Found: This** failure **mode represented** 0.3% of all CCAS tested in both LESS and HASS for failures that manifested themselves as no defect found,

Comparing the ratio of the failures to the total sample sizes for margin failures, HASS was more effective than LESS (0.9% versus 0.45 %) at precipitating margin-related failures. This greater effectiveness was believed to be attributed to the differences in the thermal characteristics of the screens. In particular, the higher thermal capacitance of the LESS fluid resulted in more uniform product temperatures during LESS testing as compared to HASS testing. As a result, some component temperatures during HASS ran slightly hotter, and some slightly cooler than in LESS, given the same thermal ambient conditions. These temperature differentials were believed to affect the performances of the components so that their interoperability was compromised.

Table 5-1. Product 3 VASE Matrix for* HASS *Process

[ASS Stresses Plus Functional Failures (i.e Dead-On-Arrivals)	Number of Failures Found per Failure Mode/Mechanism: Timing	Functional Failure/Wrong Output		Short	Stuck Bit (Cracked Die)	No Defect Found		Cold Solder Joint	Solder Ball	Solder Bridge	Solder Wetting	Flux Cleaning	Coplanarity	Handling	In-Circuit Test (ICT) Skipped	Interrupt	Parameter Drift	Others	Total Failures Detected by Each Knob	Defect costs: Relative Cost/Defects Detected by Screening Stress
:unctional Test (DOA)	3			2	1			1	1			9	i	4	1	i			24	$1
>old Level	2	4	2			1	1	2			.								12	$7
>old/Low Voltage	3	2	1																6	$7
/ibration or Hot/Vibration		1		1						1	2						1		6	$55
Hot Level or Ramp Rate	1	2			1	1													5	$33
>old/High Voltage	1	2																	3	$14
Hot Level	2																		2	$41
Hot/High Voltage			2																2	$21
>old/Negative Ramp	1		1																2	$21
{et/Low Voltage			2																2	$21
Ramp Rate			1																1	$41
Hot Dwell or Hot After Vibration						1													1	$83
/lultiple Thermal Cycles						1													1	$5,03
otal Failures per Mode Found **by All Knobs**	[illegible]	11	9	3	2	4	1	3	1	1	2	9	1	4	1	1	1	0	67	S200

Note: There were six failures in the Failure Analysis Database where no HASS data was available

Table 5-2, Product 3 VASE Matrix for LESS Process

LESS Stresses Plus Functional Failures (i.e., Dead-On-Arrivals)	Number of Failures Found per Failure Mode/Mechanism: Precipitated but No Defect Found	No Defect Found	Timing	Stuck Bit	Functional Failure/Wrong Output	Unknown	Short	Solder Reflow	Insufficient Solder	Cold Solder Joint	Solder Bridge	Solder Wetting	Flux Cleaning Process Failure	Open Trace Inside Board	Mishandling	Part Placement	ICT Skipped or Faulty ICT	Connector Shorted	Unknown	Parameter Drift	Total Failures Detected by Stress	Defect Costs: Cost/Defect Detected by Screening Stress
Functional Tes! (DOA)					1									1	-7	1	1	1	2		14	$17
Other Categories Transition Cycles, Cold Parameters. Hot Parameters, In Air			1	2										1					5		9	$687
Hot Level				2				1													3	$79
Cold Level					2																2	$119
in Air and High Voltage Testing			2																		2	$119
Hot and Low Voltage			-i-																		1	$238
Total Failure Modes Found by All Stresses			4	4	3			1						2	7	1	1	1	7		31	$215

Note. Numerical entries area count of the failures detected during the LESS testing

Table 5-3. VASE Matrix Comparison for HASS and LESS Processes [1] (by Tall-Pole Failure Mode)

	Timing	Functional Failure/Wrong Output	Short	Stuck Bit (Cracked Die)	Solder Defects (Reflow + Insufficient Solder + Cold Joint + Bridge + Wetting)	Failure Not Reproducible or Unknown [2]	Parameter Drift	Open Trace Inside Board	Wire Shorted	**Overall Including No Defect Found and Unknown**	**Overall Excluding No Defect Found and Unknown**
Ho= HASS is equal or better than LESS	90%	84%	82%		82%		74%		74%	32%	82%
Ho= LESS is equal or better than HASS				99%		96%		94%		68%	18%

Notes: [1] The Dead-on-Arrival category was not included in data
[2] The significance of the categories "Failure-Not-Reproducible" and "Unknown" is not clear.

Table 5-4. VASE Matrix Comparison for HASS and LESS ***Processes (by Failure*** Manifestation ***Modes)***

	Margin	Precipitated	Margin (not reproducible)	No Defect Found	Precipitated (not reproducible)
Ho= HASS is equal or better than LESS	96%			61%	
Ho= LESS is equal or better than HASS		63%	98%		73%

Note: The Dead-On-Arrival category was not included,

Table 5-5, Product 3 HASS/LESS **Overall Yield**

Statistic	HASS	LESS
Number of cards screened	3661	1555
Number of cards failed	60'	23*
Yield	98.36%	98.52%
Confidence interval (95°/0)	0.5%	0.7%
Escapes (estimated)**	0	0.12%

' Includes NDF does not include DOA or design errors.
.* Escapes into HASS (from LESS)

Table 5-6. Product 3 HASS and **LESS Failure Comparison**

Failure	HASS Percent of CCAS Failed	HASS Percent of CCAS Total Tested	LESS Percent of CCAS Failed	LESS Percent of CCAS Total Tested
DOA	28.6	0.65	37.8	0.9
Margin	39.3	0.9	18,9	0.45
NDF	13.1	0.3	16.2	0.39
Precipitated	14.3	0.33	10.8	0.26
Precipitated (non reproducible)	1.2	0.08	13.5	0.32
Margin (non-reproducible)	3.6	0.03	2.7	0.06

Table 5-7. ***Product 3 Normalized Comparison*** **Between HASS and LESS [1,2]**

Screen	Failure Modes and/or Mechanisms (Precipitated and Margin Failure Only)																					Defect Costs
	Timing	Functional Failure/Wrong Output	Failure Not Reproducible	Short	Stuck Bit (Cracked Die)	Insufficient Solder	Cold Solder Joing	Open Trace Inside Board	Solder Reflow	Solder Ball	Solder Bridge	Solder Wetting	Flux Cleaning Process Failure	Coplanarity	Handling (BDs Drooped)	Short In Connector	ICT Skipped	Part Placement	Interrupt	Parameter Drift	Others	Total Failures Detected by Knob	Cost/Defects Found (by Knob)
HASS	10	11	3	3	2	1	1				1	2								1		35	$200
LESS [3]	9	5	12		9			2	2													40	$215
Total	19	16	15	3	11	1	1	2	2		1	2								1			

Notes: [1] Data presented in Tables 5-5 and 5-6 are solely based on failure analysis data. Failures shown above are a subset of those shown in Tables 5-5 and 5-6 due to test history availability.

[2] Dead-On-Arrival and No-Defect-Found failures have been removed for this comparison.

[3] Entries shown for LESS have been “normalized” by multiplying actual counts (Table 5-2 entries)

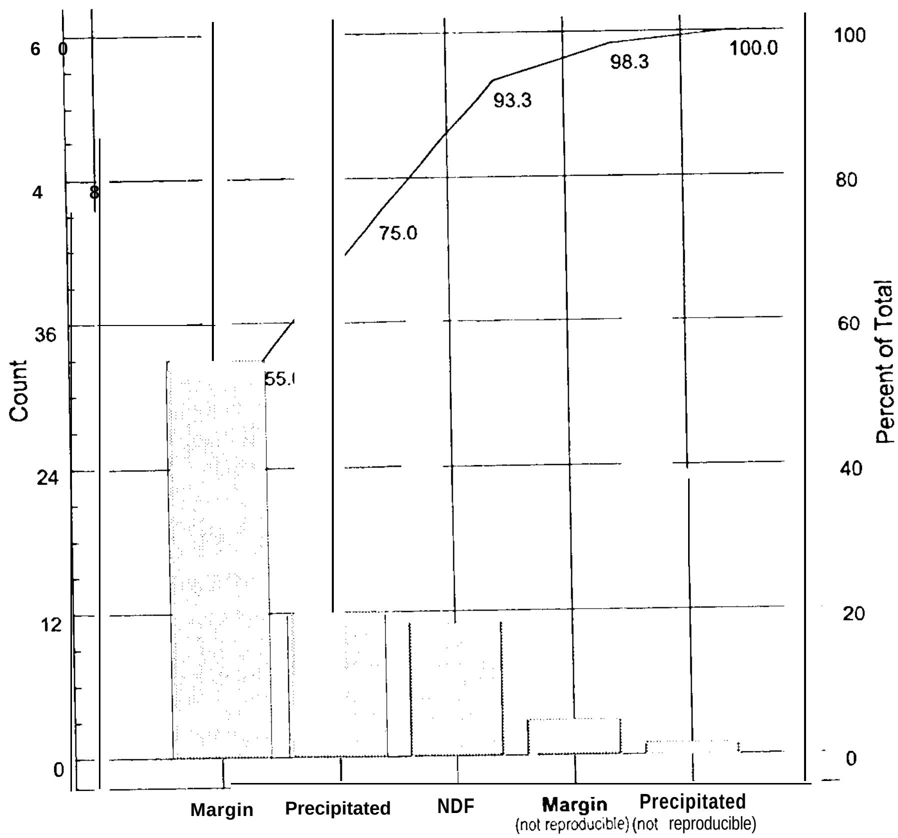


Figure 5-5. ***Pareto Chart of HASS Failures***

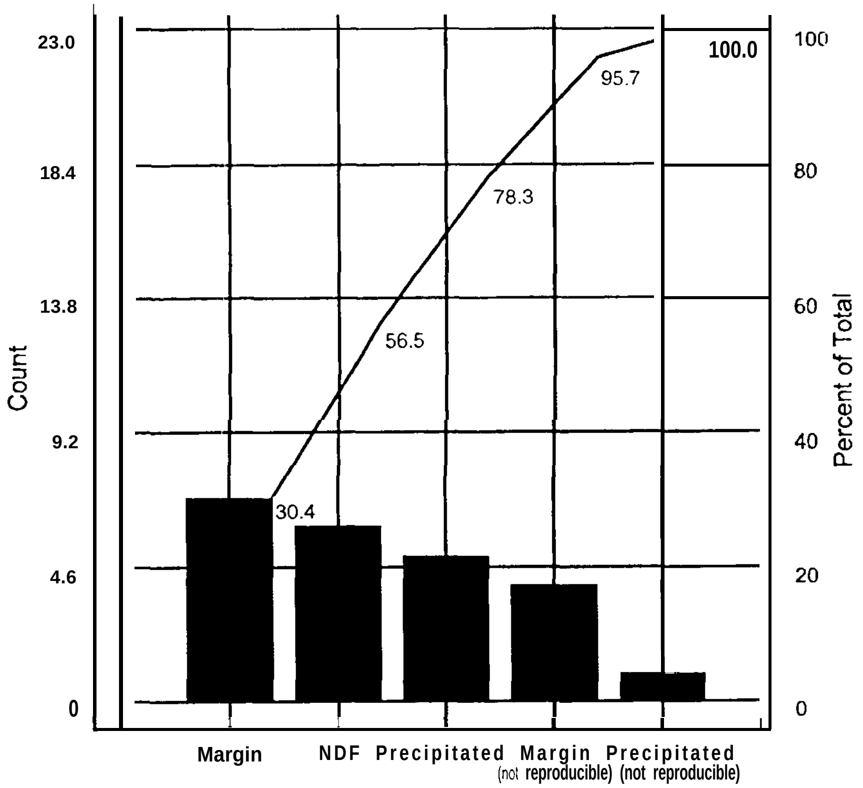


Figure 5-6. Pareto *Chart of LESS Failures*

In summary, from Table 5-3:

- The null hypotheses that HASS testing is equal to or more effective than LESS testing for failure modes related to part parameters and solder joints cannot be rejected at the confidence levels indicated in Table 5-3.
- The null hypotheses that LESS testing is equal to or more effective than HASS for stuck bits and open trace in board cannot be rejected at the confidence levels indicated in Table 5-3.
- The choice of screens can be largely affected by failures that were either false positives (No Defect Found) or nonreproducible.

As shown in the VASE matrices, Tables 5-1 through 5-4 and 5-7, the failures were categorized according to failure modes or mechanisms. HASS was found to be 2.5 times more effective at precipitating manufacturing workmanship failures (i.e., cold solder joints) than LESS. This large difference was attributed to the use of vibration during the HASS screen which the LESS screen does not provide.

Finally, LESS was about 12 times more effective at precipitating component-related failures (i.e., die contamination) than HASS. The high thermal ramp rates of LESS appeared to be the significant factor that HASS could not replicate. LESS also precipitated board copper failures that HASS did not identify.

The VASE matrices show the failure modes or mechanisms and the environmental stress or stresses necessary to precipitate these failure modes or mechanism. Also, the last column of Tables 5-1, 5-2, and 5-7 shows cost figures for the various environmental stresses specific for the Product 3 process. The VASE matrices in Tables 5-3 and 5-4 present another way to examine the data discussed earlier in this section. In Tables 5-1 and 5-2, however, the granularity of the type of screen is increased. Instead of showing the relationship between the screen and the failure mode or mechanism, the VASE matrices relate the stresses (i.e., cold temperature, vibration, etc.) of the screens to the failure mode or mechanism. Viewing the data in this way, it is possible to identify the most “capable” stresses for the failure modes or mechanisms of interest.

By analyzing the existing ESS process for Product 3, significant improvements were proposed for the Product 3 HASS screen. In particular, the screen cycle time and LN2 consumption could be reduced by 50 and 66%, respectively. Given the significant volume of Product 3 CCAS produced, these reductions, if successful when implemented, would result in significant cost savings over the existing screening process. Figure 5-7 shows the enhanced HASS profile.

5.4 Cost Analysis

A cost analysis was performed to determine which process was most effective during screening (see Table 5-8).

5.5 LESS Conclusions

Based upon the results described above, several conclusions may be drawn for Product 3:

- The HASS process surfaced nearly all failures in the first thermal cycle, while in the LESS process, failures were distributed over the 10 cycles used.
- LESS was about 12 times more effective at precipitating part- or die-related latent defects than HASS. This difference maybe attributed to the significantly higher thermal change rates associated with LESS.
- Application of the VASE methodology and process indicates the potential for process optimization. In particular, a potential run cycle time reduction by 50% and an LN_2 reduction by 66% seems achievable.

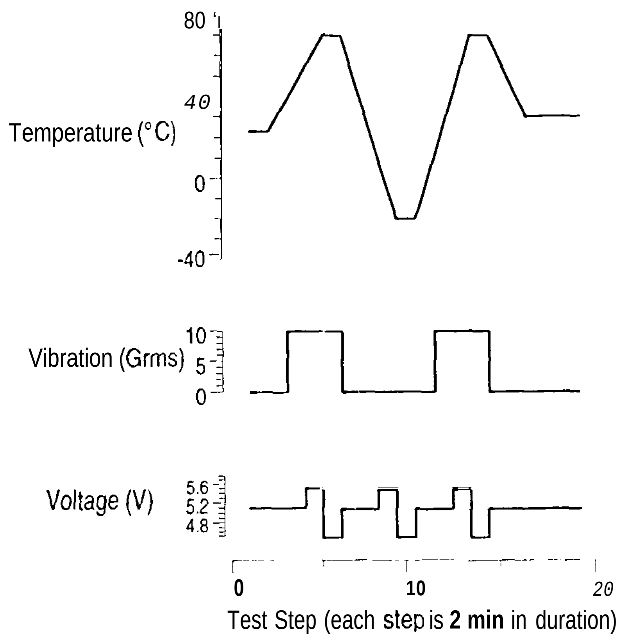


Figure 5-7. **Enhanced *HASS* Profile Generated from HASS VASE *Matrix***

***Table** 5-8. Screening Cost Effectiveness*

	Volume in Units								
	5,000			10,000			15,000		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
HASS	x1	X2 = 0.83x 1	0.83 x1	x3	x4= 0.86 x 3	0.86 x 3	x 5	x6 = 0.89 x 5	0.89 x 5
LESS	1.12X1	1.34x2	0.76 X 2	1.09X3	1.26x4	0.80 X 4	1.08 x 5	1.22 x 6	0.83 x 6
LESS Savings or (Cost), %	(12)	(51)	7.3	(9.6)	(40)	6.3	(8.0)	(33)	5.6

Notes: x(n) = Cost to perform baseline screen for the cases and volumes shown

Case 1: New environmental equipment

Case 2: Baseline (HASS) equipment fully depreciated; new LEST equipment

Case 3: All equipment fully depreciated

- The HASS and LESS exhibited virtually identical overall process yields of 98.36 and 98.52%, respectively.

- LESS and HASS durations used were approximately the same. The throughput of the CCAs in HASS, however, was higher due to the greater capacity of the HASS machine compared to the LEST machine.

- The increased thermal capacitance of the LESS working fluid is believed to have resulted in smaller temperature variations across the product than in HASS.

- HASS was 7.5% less expensive to perform than LESS. Given similar yields between LESS and HASS, HASS is less expensive if purchasing new equipment, and LESS is less expensive if using fully depreciated equipment.

- H ASS was 2.5 times more effective at precipitating manufacturing latent defects (i.e., cold solder joints) than LESS. This difference may be attributed to the use of vibration during the HASS screen which the LESS screen does not provide.

- The safety of screen process showed that LESS had no detected adverse effects on the technologies tested up to 300 thermal cycles.

6. The Database

The raw data from the Environmental Stress Screening (ESS) 2000 Project was gathered and stored in a shared project proprietary database. The database allowed standardized coding of data so that information from the various sources could be compared and analyzed. The data included: (1) failure summary reports, (2) timeline events, and (3) product and process descriptions. The database linked data from various applications, such as Microsoft" Excel data sheets, Microsoft® Word documents, and Microsoft Access" files, which could be automatically opened from the database. The database was created with FileMaker Pro™ and was intended for the participant companies to use for future reference with the potential for accumulating new data for ongoing analyses. Block diagrams representing the processes used to evaluate each technology are supplied with the ability to "drill down" to lower level details.

6.1 Participant Baseline Processes

Since the participants represented a variety of industries (see Subsection 1.2, Table 1-1), it was important to understand the baseline testing philosophy of each organization. Each participant procures, manufactures, inspects, qualifies, and accepts hardware according to its own unique requirements. This section of the database highlighted the basic philosophy of each participant company that supplied product for the study. Block diagrams of the evaluating participants' current baseline ESS methods are in the Technologies Studied section of the database for comparison purposes.

6.2 Product Descriptions

A short description of the products subjected to each ESS method is included in the database. Part count, part types, power, weight, dimensions, and hardware function are some of the descriptive elements supplied. More detailed descriptions can be found in various portions of this report.

6.3 Participant Baseline Process Data

Data was extracted from three of the project participants' factory data collection processes to record a baseline of current methods and effectiveness for the technologies in practice at each facility. This data did not play a direct role in the ESS evaluation, but was gathered in case any questions arose during the analysis phase of the project.

6.4 Safety of Screen Data

The results of the safety of screen activities are summarized in subreports that are accessible from the Reference Files section of the database. The subreports identify the applicability and utility of the various alternatives evaluated.

6.5 Evaluation Data

The data gathered during the alternative ESS evaluation phase was stored in the same part of the database as the baseline data, but was coded so that it could be easily parsed. Although the statistical sample sizes for this data varied, each participant's experience and ESS process expertise provided valuable lessons learned. The assumptions and observations made during this phase are summarized in the database. The Value Added Screening Effectiveness (VASE) matrix (see Section 8 of this report) can be accessed by opening the appropriate VASE file in the Files Section of the database. Other reports are available that can also provide information on test effectiveness, failure mode trends, and other summary information.

6.6 Reference Files

Numerous data sheets, subset databases, comments, documents, scanned images, subreports, and others were generated during the project. Each file is accessible directly from the database by selecting the file of interest from a files list, then clicking the open button.

6.7 Lessons Learned from the Development of a Standard ESS Database

The usefulness of the database containing the necessary data to evaluate ESS methods would be extremely valuable for the continued improvement of the way in which industry selects and improves the proper ESS techniques for products. To maximize the collaborative knowledge of all of industry requires the coordination of the data necessary to perform evaluations.

The ESS 2000 Project acquired data from the participant companies. Although this data was similar, a great effort was made to merge the various data sources into a single uniform database. A standard set of data requirements in the form of an electronic data interchange (EDI) template would have solved this problem, and the data would have been extremely easier to collect, collate, and analyze. The project did establish a common set of terms and data requirements; however, when the data was retrieved from existing databases, the mapping of that data was very time intensive. Again, the data gathering would have been a minor task if EDIs had been in place. Although the database has simple summaries, the time saved in combining the data could have been better spent developing analytical tools.

Cost Model

The Environmental Stress Screening (ESS) 2000 Project cost model was used to compare and contrast the costs of performing various stress screens. When the cost model is combined with the Value Added Screening Effectiveness (VASE) matrix, screen attribute costs can be determined and ultimately optimized, The participants gathered cost data on their respective ESS processes. This information was combined and analyzed to compare the cost differences among the four processes.

To determine the ESS cost per unit/box for each ESS technology, the following assumptions and parameters were used in the model:

- A three-year quarterly time period was used for calculating costs. The actual cost per unit/box was determined by dividing the total ESS costs for the three-year period by the total number of units screened during the same period,
- Labor in man-months was input by quarter (a total of 12 quarters for the three-year period) for technician support to run the test and engineering support for any test equipment problems. The yearly salary in direct dollars was also input for both technician and engineer.
- The time period chosen for capital depreciation was 10 years. Items associated with capital depreciation were: chamber cost in dollars, vibration table cost in dollars, and test equipment cost in dollars. Three different cases were chosen for comparison purposes.
  - Case 1: The cost of new environmental equipment was included in the first quarter for each ESS technology and allowed to depreciate over the chosen three-year period.
  - Case 2: Baseline environmental equipment was assumed to be fully depreciated (cost not included) while the alternative environmental equipment was considered to be new, included in the first quarter, and allowed to depreciate over the chosen three-year period.
  - Case 3: The environmental equipment for each ESS technology was considered to be fully depreciated (cost not included).
- Consumables input into the model were electricity in kilowatt-hours per run and liquid nitrogen (LN_2) usage per run in gallons. The cost per kilowatt-hour and per gallon of LN_2 were also input.
- The costs of facility installation and fixturing for vibration and temperature cycling were also included in dollars during the first quarter.
- The maintenance costs in dollars associated with the chambers and vibration tables were included in each of the 12 quarters.

8. Value Added Screening Effectiveness (VASE) Matrix Process

The application of the VASE methodology and process was derived from the work being done at Jet Propulsion Laboratories (JPL) on physics-of-failure-based tests [1, 2, 3, 4].* The VASE process was used as the method to determine the effectiveness of the Liquid Environmental Stress Screen (LESS) and Highly Accelerated Stress Screen (HASS) processes for Product 3. Application of the VASE process enabled optimization trade-offs among various design and verification activities as well as optimization of screening processes. Specifically, the VASE matrix organized data by failure mode and/or mechanism and screening parameter to determine the effectiveness of a given set of stresses (or a single stress parameter) in detecting a given failure mode and the number of those failure modes present in a design. The output of this process is shown in the VASE application for Product 3 in Section 5.3.

8.1 VASE Subprocesses

The VASE process has four major subprocesses:

1. Failure data classification
2. Cost determination
3. Optimization
4. Closed loop feedback.

in one form or another, these processes take place in most organizations. When the VASE process is implemented, it simply ties them all into a single linked process enabling optimizations to be made.

8.1.1 Failure Data Classification Subprocess

The failure data classification subprocess involves classifying the data in three ways and then summarizing the data in these classifications. The first category is the way in which the failure manifests itself. For example, the article under test fails after having been exposed to a particular stress (or set of stresses) or only fails under a certain combination of stresses. The second category addresses the failure code, mode, and/or mechanism that was detected during the ESS and subsequent failure analysis processes (e.g., open, short, out of timing, etc.). The last category identifies the stress or combination of stresses that were responsible for detecting each failure code, mode, or mechanism. The data was summarized for each classification.

Latent defects are typically precipitated by the application of a more severe stress or set of stresses. Two categories of latent defects were considered: precipitated defects and margin defects. For precipitated defects (i.e., hard failures), the order in which the stresses were applied was usually relevant; however, margin failures were independent of stress order. Margin failures were typically timing failures or out-of-specification performance types. The process for determining which stress or combination of stresses were responsible for detecting a flaw was easy for margin-type failures.

8.1.2 Cost Determination Subprocess

The function of the VASE process, in the context of the ESS 2000 Project, was to determine the value added by performing a given screen. The top-level metric used to determine value added by a screening process was the cost-per-defect-detected. To do this, failure prevention and/or detection data was linked to data for the cost of the activity being evaluated. The project cost model was executed by all participant companies to determine their individual costs for performing the baseline and alternative ESS processes under evaluation. The overall value added by a screening process was determined by dividing the number of defects detected by the cost of detecting defects.

* Numbers in brackets indicate references listed in Subsection 8.2.

8.1.3 Optimization Subprocess

The output of the cost determination subprocess was a top-level metric on the cost-per-defect-detected. In the optimization subprocess, one of two options was taken: (1) optimize the screen (i.e., minimize cost-per-defect-detected), or **(2)** compare the cost to detector prevent a defect at various points in the life cycle of the hardware versus detecting it at ESS. For this project, optimizing the effectiveness of the Product 3 screen was examined (see Table 8-1). The steps to optimize a given screen are:

1. Divide screen into its constitutive parts. Use the stress classification process to identify the appropriate constitutive parts.

2. Allocate total screen cost. Use the test time line (and the cost model) to allocate the total cost to perform a screen among the stresses determined in Step 1. The output of this will be the cost to perform or create the individual stresses per product under test.

3. Link failure classification data to cost data. Link the cost data of Step 2 to the effectiveness data from the failure classification process by multiplying the costs identified in Step 2 by the number of articles that underwent test, then divide by the number of defects detected in the test population.

4 Rank the cost effectiveness of the various stresses. List the stresses in order of the cost-per-defect-detected from lowest to highest.

Table 8-1. Product 3 VASE Matrix for HASS Process

{ASS Stresses Plus Functional Failures (i.ε Dead-On-Arrivals)	Number of Failures Found per Failure Mode/Mechanism																		Defect Costs
	iming	Functional Failure/Wrong Output	Unknown	Short	Stuck Bit (Cracked Die)	No Defect Found	Insufficient Solder	Cold Solder Joint	Solder Ball	Solder Bridge	Solder Wetting	Flux Cleaning Process Failure	Coplanarity	Handling	In-Circuit Test (ICT) Skipped	Interrupt	Parameter Drift	Others	Total Failures Detected by Each Knob	Relative Cost/Defects Detected by Screening Stress
·unctional Test (DOA)	3			2	1			1	1			9	i	4	1	1			24	$17
ɔold Level	2	4	2			1	1	2											12	$7(
ɔold/Low Voltage	3	2	1																6	$7(
/ibration or Hot/Vibration		1		1						1	2						1		6	$55(
⊣ot Level or Ramp Rate	1	2			1	1													5	$33!
;old/High Voltage	1	2																	3	$14(
-lot Level	2																		2	$41!
⊣ot/High Voltage			2																2	$21(
ɔold/Negative Ramp	1		1																2	$21(
-lot/Low Voltage			2																2	$21(
Ramp Rate			1																1	$41'
Hot Dwell or Hot After Vibration						1													1	$83
Multiple Thermal Cycles						1													1	$5,03
ſotal Failures per Mode Found **by All Knob**	13	11	9	3	2	4	1	3	1	1	2	9	1	4	1	1	1	0	67	$200

NOT E: There were six failures in the Failure Analysis Database where no HASS data was available

5. Make trade-off decisions. Identify candidate stresses/combination of stresses that have a high cost-per-defect-detected or stresses that detect failure modes/mechanisms that can be more cost effectively detected by other stresses.

6. Implement trade-off decisions. implement the findings of Step 5 to obtain an optimal solution. In some cases, it may be more cost effective to detect defects in an earlier or later activity. If the cost effectiveness of these earlier or later activities has also been analyzed by the VASE process, then optimization trade-offs can be made among the whole set of activities or screens. In other cases, it may be more cost effective to increase the screening strength (i.e., stress level) in one test while eliminating it in others.

8.1.4 Closed-Loop-Feedback Subprocess

To measure the effectiveness of the changes made during the optimization subprocess, the VASE process should be integrated into the data collection system. This will then provide the metrics necessary to optimize cost effectiveness over a long-term basis.

8.2 References

1. Cornford, S. L. and M. Gibbel (1996). "Methodology for Physics and Engineering of Reliable Products." Weston/96 Conference, Anaheim, CA, October 22–24.

2. Cornford, S. L.(1996). "Defect Detection and Prevention." *Proc. 16th Aerospace Testing Seminar*, Los Angeles, CA, March.

3. Greenfield, M. A. and T. E. Gindorf (1996). "Risk as a Resource-—A New Paradigm." *Proc. Probabilistic Safety Assessment and Management '96, ESREL'96/PSAM-111*, Crete, Greece, June 24--28. New York: Springer. Eds. Carlo Cacciabue and Loannis A. Papazoglue. Vol. 3, pp. 1597-1605.

4. Gibbel, M. and J. F. Clawson (1990). "Electronic Assembly Thermal Testing–Dwell/ Duration/Cycling." *Proc. 12th Aerospace Testing Seminar,* Los Angeles, CA, March.

9. Conclusions and Recommendations

The Environmental Stress Screening (ESS) 2000 Project participants identified and evaluated four ESS technologies/processes:

- Military Environmental Stress Screening (Mil-ESS)
- Highly Accelerated Life Test/ Highly Accelerated Stress Screen (HALT/HASS)
- Electrodynamics Accelerated Life Test/Accelerated Stress Screen (ED-ACLT/ACSS)
- Liquid ESS (LESS).

Each of these technologies was shown to have some advantages over the other technologies. The key in selecting a cost-effective approach to ESS is to understand all the factors necessary for the decision on which technology to use. These factors include:

- Test philosophy to be used
- Ability to detect and determine the root cause of faults
- Packaging technology used
- Type of flaws anticipated
- Product yields
- Amount of test labor
- Volume of product being screened
- Cost of consumables
- Cost of equipment, its maintenance, etc.

Since these factors vary with each company, the results can also vary as to which screening technology is most cost effective. However, based upon the work performed in the ESS 2000 Project, some general conclusions and recommendations are provided here.

9.1 Conclusions

The project team reached the following conclusions from this study:

- The better the understanding of the latent failure mechanisms of the product technologies, the greater the ability to select and tailor a cost-effective screen.

- Products containing significantly greater piece part or die level defects than manufacturing or assembly defects were most cost effectively screened with LESS. On the other hand, products containing significantly greater manufacturing or assembly defects were most cost effectively screened with the HASS. No single screening technology appears to be the best for all products, manufacturing processes, and packaging technologies.

- Both HASS and ED-ACSS were found more cost effective than the Mil-ESS when the maximum throughput of the ESS chamber was used.

- Both military and commercial products can be subjected to the accelerated environments of HALT/HASS without damaging the product.

- For the products tested, exposure to the fluorocarbon fluids and rapid thermal ramp rates occurring in the LESS process did not create failures in, or change the appearance of, the product. Product compatibility with LESS was observed when the product contained materials that were undamaged by exposure to the fluid, did not entrap fluid, or cause improper product operation.

9.2 Recommendations

- ESS information should be collected, analyzed, and shared across the electronics industry in a collaborative process to improve industry knowledge of product reliability and reduce product costs.

- The applicability of Value Added Screening Effectiveness (VASE) to other manufacturing processes (i.e., in-circuit test [ICT] and functional test) should be examined.

- Field failure data should be obtained to further verify the effectiveness of the ESS processes.

- The interactions between failure mechanisms and environmental stresses should continue to be investigated.

- An industry-wide vehicle for exchanging ESS data should be developed.

Appendix A: Product Descriptions

Al. Product 1

Product 1 consists of four circuit card assemblies (CCAS) housed in an aluminum housing or box. The approximately 8 in. x 18 in. CCAs are 8 to 12 layers thick and are made of FR-4 Tetra II material. Each card contains approximate y 900 through-hole components, which are conformal coated. The CCAs are flow soldered according to MIL-STD-2000, Rev. A. The assembled box weighs approximately 35 lb. Circuit card component types are shown in Figure A-1, and the components list is given in Table A- 1.

A2. Product 2

Product 2 consists of a single CCA housed in an aluminum housing. The unit is 12.2 in. x 9.2 in. x 2.8 in. high and weighs 5.4 lb. The unit power dissipation is 21.9 W. The CCA consists of eight layers. The board material is a high-temperature epoxy, in accordance with MIL-S- 13949, type GFG, which has a glass transition temperature between 150° and 200°C. The surface finish of the CCA is plated and reflowed tin-lead. The CCA has a localized heat sink or thermal plane bonded to it for heat sinking some higher power dissipating devices. This local heat sink is located in the 1/0 connector area of the card. The CCA is a Type II assembly consisting of both surface mount devices and through-hole devices. The percentage of through-hole versus surface mount devices is shown in Figure A-2.

The CCA has 728 electrical parts. The percentage of each part type is shown in Figure A-3. A component type list is shown in Table A-2. Plastic encapsulated components are used throughout the assembly. Large components, for example, large cylindrical capacitors, are bonded with an epoxy material to the CCA for structural rigidity. The topside surface mount components were assembled onto the card by either hand soldering or convection reflow soldering in air. The bottomside surface mount components and the through-hole components were assembled by wave soldering in air. Second assembly components were assembled by hand soldering. The CCAS were conformal coated with an acrylic conformal coating material.

A3. Product 3

The boards used in this phase of testing perform serial-to-SCSI data conversion for hard drive assemblies. The boards, measuring 6 3/16 in. by 5 5/8 in., are constructed of FR-4 material and consist of six layers: two ground planes and four signal layers. The boards are populated by the component types and information shown in Table A-3.

Product 3 undergoes a typical combination surface mount technology (SMT)/through-hole manufacturing and test process. Figure A-4 shows a high level manufacturing flow diagram of this process.

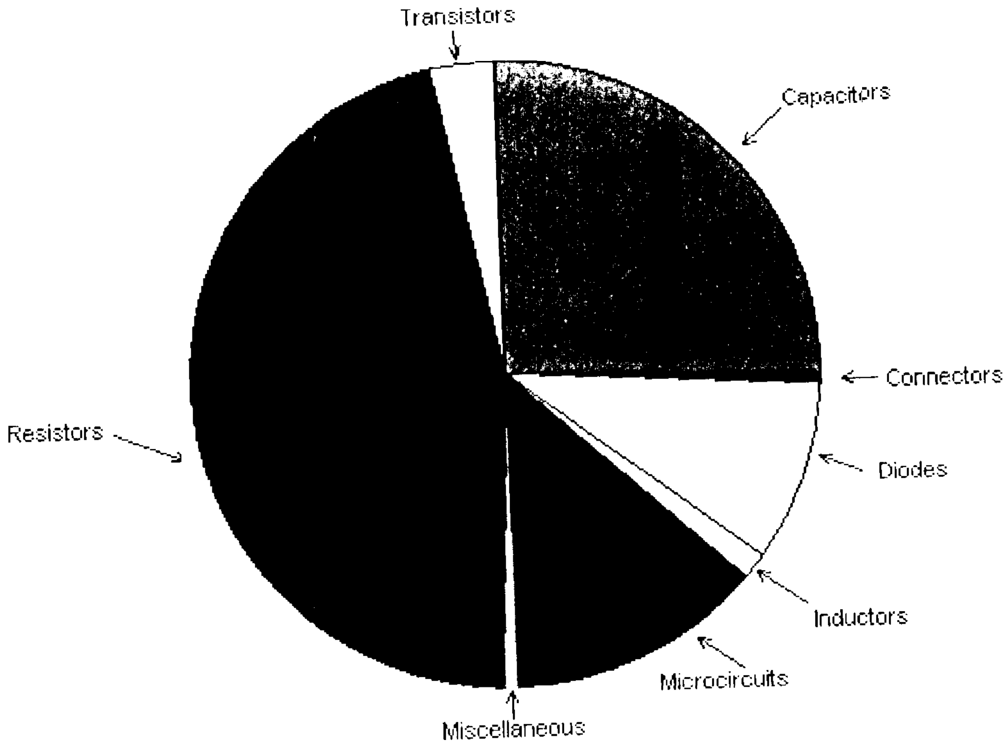


Figure A-1. Product 1 Component Part Types

Table A-1. Product 1 Component Type List

Package Style	Package Type	Military/industry/ commercial	Part Type	Part Technology	Hermetic/ Non-Hermetic
Axial Lead	Through Hole	Military	Capacitor	Ceramic	Hermetic
Axial Lead				Electrolytic	
Radial Lead					
122 Contacts			Connector	PWB Connector	Non-Hermetic
20 Contacts					
50 Contacts				Submini	
53 Contacts				pWB ConneCtOr	
80 Contacts			Digital IC	Bipolar	Hermetic
14 CDIP				CMOS	
14 CDIP				Silicon	
14 CDIP				CMOS	
16 CDIP				Bipolar	
16 CDIP					
20 CDIP					
24 CDIP				CMOS	
24 CDIP					
24 TCDIP				TTL/CMOS	
28 CDIP				CMOS	
40 CDIP					
68 PGA					

Table A-1. Product 1 Component Type List (Continued)

Package Style	Package Type	Military/Industry/ Commercial	Part Type	Part Technology	Hermetic/ Non-Hermetic
8 CDIP	Through Hole	Military	Digital IC	Bipolar	Hermetic
TO-3					
TO-39					
DO-13			Diode, SEMI	Silicon	
DO-204					
DO-35					
DO-41					
DO-7					
CAN			Inductor	Audio	Non-Hermetic
CAN, Brass					
CAN, Mumetal					
14 BBDIP			Linear IC	CMOS	Hermetic
14 CDIP				Bipolar	
14 CDIP				BIFET	
16 CDIP				Bipolar	
16 CDIP				CMOS	
16 SBDIP				Bipolar	
20 CDIP					
28 CDIP					
36 SBDIP				Hybrid	
8 CDIP				Bipolar	
8 CDIP				BIFET	
8 CDIP				CMOS	
84 PGA					
TO-3				Bipolar	
TO-39					
TO-4					
TO-46					
TO-8					
TO-99					
14 CAN			Oscillator	Crystal	
8 CAN			Relay	DPDT	
Axial Lead			Resistor	Wirewnd	
Axial Lead				Film	
Axial Lead				Thermal	
Axial Lead				Wirewnd	Non-Hermetic
Radial Lead				Film	Hermetic
Radial Lead				Wirewnd	
SIP			Resistor, NTWK	Thick Film	
ROD			Switch	Thermo	
8 CAN			Transformer	Pulse	
9 CAN					
TO-18			Transistor	Silicon	
TO-205					
TO-39					
TO-72					

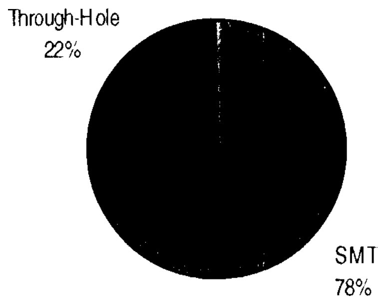


Figure A-2, Product 2 Package Type

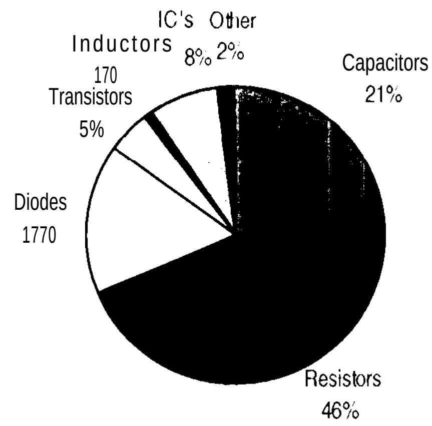


Figure A-3. Product 2 Part Types

Table A-2, Product 2 Component Type List

Package Style	Chip Package Type	Military/Industry/ Commercial	Hermetic (H)/ Non-Hermetic (NH)
1206 Chip Capacitor	SMT	Military	NH-Ceramic
1210 Chip Capacitor			
1505 Chip Resistor			
14 Sole		Commercial	NH-Plastic
16 SOIC		Industry	
208 PQFP			
28 SOIC			
28 SOJ			
32 PLCC			
44 PLCC			
8 SOIC		Commercial	
Diode		Military	
DPAK			
SOT 23			
SOT 89			
Diode	Through Hole		H
16 CDIP			H-Cerdip
8 CDIP			
8 MC			H-Metal Can
TO-5			
TO-46			
14 DIP			H-Metal Case
Capacitor			
Diode			
RF/EMI Filter			
Fuse			NH
Diode			
Resistor			
Inductor			NH-Plastic
Transformer			
Capacitor			
TO-220		Industry	
TO-247		Military	

Table A-3. Product 3 Component Type List

Package Style	Chip Package Type	Military/Industry/ Commercial	Plastic/ Hermetic
60 pin connector	Through Hole	Industry	Plastic
14 Sole	SMT		
0603 Resistor			Ceramic
2512 Resistor			
0805 Resistor			
1812 Capacitor			
1206 Capacitor			
0805 Capacitor			
Diode - Schotty			
1206 Inductor			
EMI falter			
32 SOIC - J lead			Plastic
8 SOIC - Gull Wing			
32 PLCC			
Crystal Oscillator			N/A
14 Resistor Pack			Plastic
20 PLCC			
28 PLCC			
80 PQFP			
160 PQFP			
20 Sole			
208 PQFP			
24 SOIC			

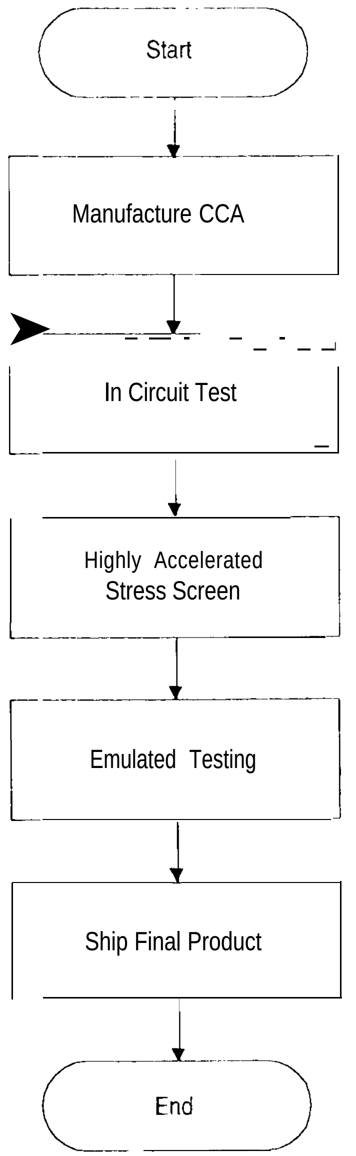


Figure A-4. Product 3 Manufacturing Flow Diagram

Appendix B: Thermal Considerations for Liquid Environmental Stress Test (LEST)

The information in this appendix was contributed by Paul Englert of Lucent Technologies.

One of the main goals of the Environmental Stress Test (EST) is to stress product to precipitate flaws in weak product so that these flaws may be corrected before shipment to a customer. One way that thermal stressing can precipitate flaws is by creating stresses in circuit card joints such as solder joints, wire or ball bonds on chips, or wired connections. Electronic components and circuit cards are usually made of materials that have different coefficients of thermal expansion (CTE). The CTE of a material describes the change in length per unit length for a temperature excursion, and is given in units of parts per million per degree Centigrade or Fahrenheit (ppm/°C or ppm/°F). For example, the electronic module shown in Figure B-1 has components with cases made of ceramic (CTE = 6 ppm/°C) mounted on a heat sink of aluminum (CTE = 23 ppm/°C).

As the environment that the module resides in undergoes a temperature change, the aluminum heat sink will tend to expand more than the ceramic portion of the component, Much research work has shown that stresses proportional to the temperature change will arise in the component's solder joints [Hall 1987; Clech and Augis 1989; Kotlowitz 1987]. (References are listed at the end of this appendix.) The key finding of the solder joint research can be summarized by the following expression:

$$Force = F = K\,L\,\Delta\alpha\,AT, \quad Stress = F/A \qquad \text{[Eq. 1]}$$

Here,

- F = shear force in the solder joint
- K = stiffness of the component in the longest (diagonal) dimension from its neutral (center) axis
- L = longest dimension from the neutral axis to a corner lead
- Act = CTE difference between the ceramic case and the aluminum heat sink
- ΔT = change in temperature from the initial ambient condition
- A = joint's projected area onto a solder pad on the substrate.

Much of the past research work has focused **on** the fatigue failure that may result in *good*

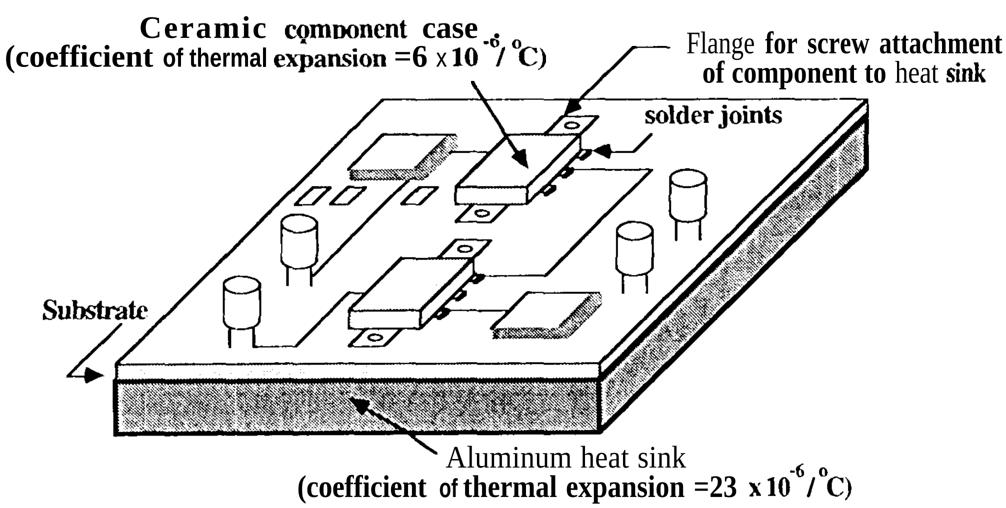


Figure B-1. Circuit Card Module With Coefficients of Expansion for Materials quality solder joints after *many* daily thermal excursions that occur throughout the life of a product. However, if flawed joints exist on a circuit module, Equation 1 may be used to estimate the stress that will be transmitted to joints during a few EST cycles. Thus, for a given circuit module, a relatively higher temperature change from ambient conditions will lead to a relatively higher stress in the component's solder joints.

Figure B-2 illustrates the thermal profile for a circuit module similar to the one in Figure B-1 subjected to LEST. A total of 20 cycles were applied to the module, and a magnified view of one of the LEST thermal cycles is exhibited. Note that the low-mass solder joint heats up and cools down faster than the component, and the component heats and cools faster than the large-mass heat sink.

Thus, for brief periods of time in each thermal cycle, there is a substantial temperature rate of change and an attendant temperature difference between the circuit module constituents. These large thermal ramps create large stresses not typically seen in normal usage environments and help to expose weaknesses in component attachments. If the same circuit module were exposed to air-based rather than liquid-based EST, the temperature change rates would be much more gradual and the stresses in joints would tend to be lower.

However, the primary advantage of LEST versus air-based thermal stressing rests in the ability to reach temperature extremes in a much more compressed time. To demonstrate this point, assume that we have an aluminum cube that is 2 in. on each side. Suppose that the aluminum cube at some temperature is suddenly submerged into a flow stream at a different temperature. For materials with a high thermal conductivity such as aluminum, the heat transfer from the fluid to the object can be modeled with a lumped capacitance *model* [Incropera and Dewitt 1981].

The heat transfer from convection of fluid flowing over the cube must balance the internal heat transfer needed to change the cube's temperature. The following differential equation describes the energy balance:

$$Force = F = K\,LAM\ \text{AT},\ Stress = F/A$$

$$-12A(7 - T_\infty) = mc\frac{dT}{dt} \qquad \text{[Eq. 2]}$$

Here,

- $11 =$ heat transfer or convection coefficient
- $A =$ surface area of the block
- $T =$ actual temperature of the block at any point in time
- $T_\infty =$ temperature of the fluid
- $m =$ mass of the block
- $c =$ the specific heat of the block
- $dT/dt =$ time rate of change of the block's temperature.

The differential equation may be solved by using the conditions that the initial block temperature is T_i and the fluid temperature remains at T_∞. The resultant expression for block temperature is:

$$Force = F = K\,L\,\Delta\alpha\ \text{AT},\ Stress = F/A$$

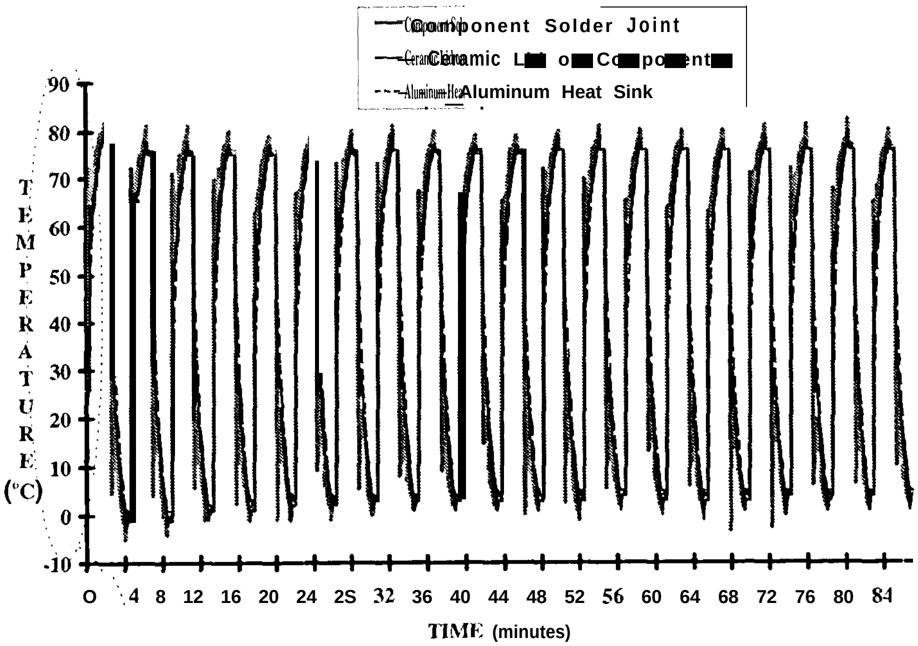
$$4A(T - T_\infty) = mc\frac{dT}{dt}$$

$$\frac{7' - T_\infty}{Ti - T_\infty} = e^{\frac{-hA}{mc}t} \qquad \text{[Eq. 3]}$$

The ratio hA/mc in the exponential expression is known as the *thermal* **time constant** and is an indicator of how fast the block can reach thermal equilibrium with the fluid.

Figure B-2 shows the actual thermal profiles of the 2-in. aluminum cube to both a liquid and air flow stream. The LEST machine described previously was used to provide liquid convection, while an air-based thermal chamber was used to transfer heat to the cube. It is interesting to see that the LEST machine helps the block reach 63% of its overall temperature change in less

Liquid thermal shock regimen applied to product (20 cycles shown)



Magnified view of one liquid thermal shock cycle applied to product.

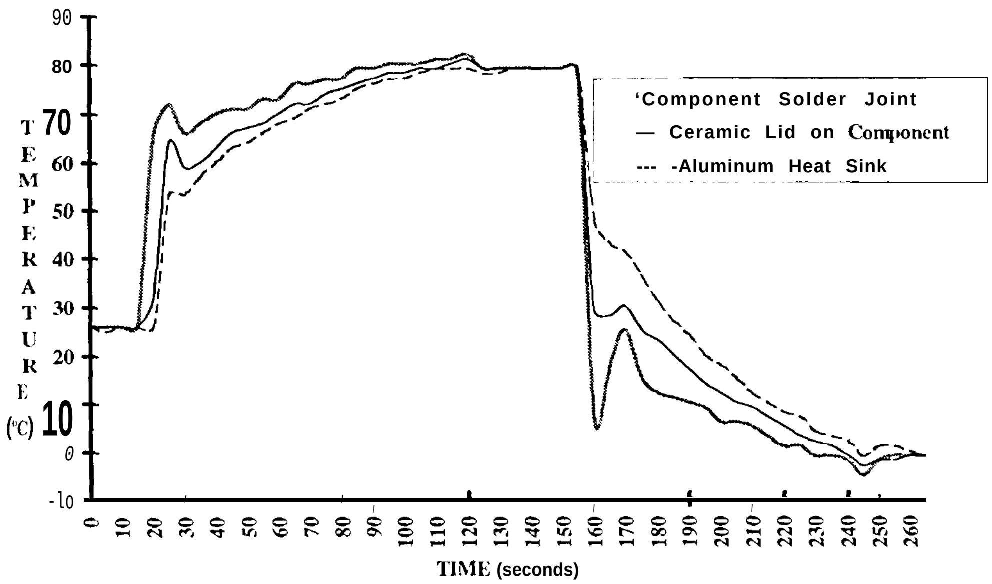


Figure B-2, *Thermal Profile of Circuit Module (From* Figure B-1 When Exposed to *LEST)* time than compared with air. Sixty -three percent of the overall temperature range corresponds to one thermal time constant; therefore, one can extrapolate a heat transfer coefficient from the numerical data in Figure B-3.

- The mass of the aluminum cube is 0.35 kg, the specific heat of aluminum is 903 J/kg ‘C, and the surface area of the 2-in. cube is 0.016 m^2.
- In the case of air, the block’s initial temperature was 20°C and the ambient air temperature was 80°C. Thus, the resultant air convection coefficient was
  h =60 W/m^2K = 10 Btu/hr ft^2 ‘F.
- In the case of liquid, the block’s initial temperature was - 10°C, the liquid temperature was 70°C. Thus, the resultant liquid convection coefficient was
  h = 183 W/m^2K = 32 Btu/hr ft^2 ‘F.

So, the LEST machine was *three times more effective* in transferring heat to the block than the air machine.

In a further comparison of the heat transfer performance of fluorocarbon liquids versus air, Incropera and Ramadhyani developed models for the heat transfer that would occur when fluorocarbons flow over electronic chips in a channel [Incropera and Ramadh yani 1994]. If we utilize the thermal conductivity of Flourinert FC-70 at 90°C and the O. S-in. chip length, the heat transfer coefficient estimate for their tests varies between 27 and 35 Btu/hr ft^2 ‘F (or 153 to 199 W/m^2 K) depending on the power dissipation. *These theoretical estimates of the heat transfer coefficient match up well with the experimental results tabulated for the 2-in. aluminum cube immersed in our LEST machine.*

Another work was performed to estimate the heat transfer rates attainable with air throughout an array of electronic components [Moffat et al. 1985]. To achieve a heat transfer coefficient in air near the *lower bound of the liquid heat transfer coefficient* (determined previously to be 27 Btu/hr ft^2 “For 150 W/m^2 K), one needs to maintain an air velocity of at least 7 m/sec (1,380 ft/min) on the surface of each component on the circuit card. Such high air velocities are difficult to maintain over circuit cards in a typical air EST chamber because of high pressure losses.

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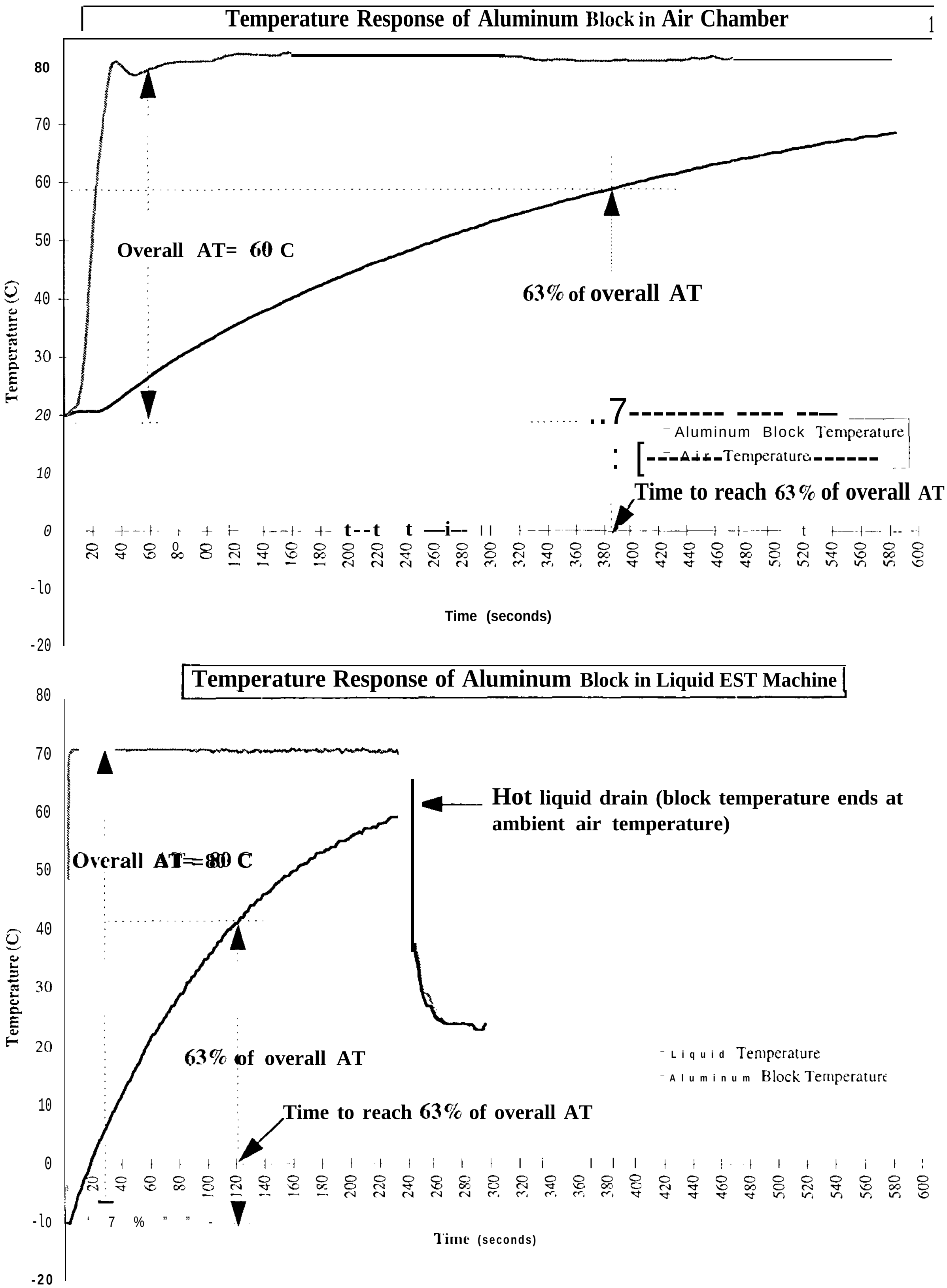

Figure B-3. Comparison of Thermal Response of Aluminum Block to *Liquid and Air Flows*

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