NAVMAT P-9492

NAVY MANUFACTURING SCREENING PROGRAM

DECREASE CORPORATE COSTS
INCREASE FLEET READINESS

MAY 1979

PREFACE

Continuing advances in electronics state-of-the-art plus increased emphasis on reliability and early development testing have increased the potential for providing a basically sound and inherently reliable design. As this potential has increased, so has the complexity and density of contemporary equipment packaging. This complexity amplifies the ever-present problems of detecting and correcting latent manufacturing defects. Equipment malfunction, after many hours of field operation, has often been attributable to something as simple as a wire which was improperly soldered. The occurrence of such a failure when equipment is installed on ship, shore, or in aircraft incurs high maintenance costs and results in low operational readiness rates.

The ability to detect simple anomalies through even the most intense visual inspection and bench checkout has become a thing of the past because of the complexity of current equipment. Effective manufacturing screens for the purpose of stimulating latent defects, whether or not such screens resemble expected mission environments, have become an absolute necessity. The manned space program of the 1960's evolved what continues to be the most cost-effective manufacturing screens: temperature cycling and random vibration. The Naval Material Command is striving to replace current and ineffective temperature cycling and low-level sinusoidal vibration with more stringent temperature cycling and random vibration in manufacturing screens such as burn-in and acceptance testing.

This report outlines, primarily for Navy contractors, an adapted and effective manufacturing screening program consisting of temperature cycling and random vibration. With the recognition that test facility cost has been a major obstacle to the use of random vibration, a technical report, which describes in detail a proven means to generate random vibration at low cost, is included as an appendix. Together, temperature cycling and random vibration provide a most effective means of decreasing corporate costs and increasing fleet readiness.

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Reliability, Maintainability
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1.0 INTRODUCTION

The reliability of a well-designed product is usually degraded to some extent in manufacturing it. A low but finite number of defects in both parts and workmanship is generally considered "normal" in manufacturing processes involving people and machines. To sustain the level of reliability inherent in the design, however, these defects must be discovered and corrected before the product leaves the factory. Otherwise, they will show up as product failures in service use with possibly serious military consequences and always with undesirable cost impact. Further, the discovery and correction of defects in the factory contributes significantly to the manufacturer's production costs, as do field returns for correction of defects under contract requirements and warranties. Both the Navy and its suppliers, therefore, have a vital interest in the most efficient and effective means for the earliest elimination of defects.

Most Navy programs acquiring electronic devices and systems traditionally have depended on the final acceptance test to catch manufacturing defects. They have relied on this screen as a sufficient incentive to the manufacturer for the inclusion of additional pre-acceptance test screens of many different forms in the production operation. Some contracts have called out specific pre-acceptance tests (e.g., burn-in) for the primary or ancillary purpose of defect detection. For a variety of reasons, both technical and contractual, the vast majority of electronic devices and systems delivered to the Navy continue to contain manufacturing defects in parts and workmanship which could have and should have been discovered and eliminated in the factory.

This publication provides guidance concerning the use of temperature cycling and random vibration as manufacturing screens for defects in both parts and workmanship. The requirements for such screens are called out in Navy instructions and reflected in contract requirements. Section 2.0 on temperature cycling is derived from a Martin Marietta report for the National Aeronautics and Space Administration on industry experience in assuring long-life hardware. Section 3.0 on random vibration has been prepared by the Grumman Aerospace Corporation under the direction of the Naval Electronic Systems Command. It summarizes the experience of Grumman and others supporting the NASA manned space program. Grumman recently has devised a technique to simulate random vibration at low cost without a sacrifice in effectiveness as a manufacturing defect screen. This technique is included as an appendix to this publication. Section 4.0 contains the minimum recommended thermal cycling and random vibration manufacturing screens to be used in the production of Navy equipment.

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2.0 TEMPERATURE CYCLING

2.1 BACKGROUND

Temperature cycling, as an acceptance test of production assemblies, is widely used as a test screen for the detection of workmanship and parts defects. It usually is used in conjunction with vibration and is particularly applicable to electronic equipment. As the design process matures, design problems should diminish significantly and approach zero. If extensive temperature cycling is employed during hardware development, as it should be, then "design" failures during the production program should be minimal, and "workmanship" and "parts" problems should predominate. The number of parts problems is influenced by the extent of the screening accomplished at the parts level. However, significant part problems are frequently detected by temperature cycling at higher levels of assembly, even when the individual parts have been subjected o high reliability screening at incoming receiving inspection.

As a part of their long-life assurance study (Reference 1) for the National Aeronautics and Space Administration, the Martin Marietta Corporation, Denver Division conducted a survey of 26 manufacturers and government agencies to review and analyze current temperature cycling practices.

Out of this came some clear guidelines for cost-effective temperature cycling as a means of stimulating latent defects for corrective action prior to delivery. Typical examples of such defects which can be screened out by temperature cycling at the acceptance test level are listed in Table 1.

Martin Marietta Aerospace
Packing problems, such as bridging of conformal coating
Shorts and opens in transformers and coils
Defective potentiometers
Intermittent solder and weld joints
Shortened power transistor
Defective capacitors
Cracked dual inline integrated circuits
Collins Radio Co.
Poor solder joints, welds, seals
Nearly shorted wire turns and cabling due to damage or improper assembly
Fractures, cracks, nicks, etc., in materials due to unsatisfactory processing
Out-of-tolerance parts and materials
NASA-MSC (Apollo)
Resistor core cracked due to absence of elastomeric buffer coating
Hairline crack in transistor emitter strap ground connection
Improper staking of tuning coil slug causing erratic output
Cold solder joints
Open within multi-layer boards due to mishandling in processing
Diode internally open at low temperatures
Drift problems
Decca Radar Limited
Defective transistor
Intermittent shorts in coils
Lugs shorted to ground
Drift and erratic operation problems
Supplier B
Problems with small gage wire (less than no. 40) in motors and other electromagnetic devices
Failure of plastic encapsulated parts
Radiation Incorporated
Drift problems
Integrated circuit problems

Table 1. Typical Examples of Defects Screened Out by Temperature Cycling

2.2 FINDINGS

2.2.1 SCOPE OF SURVEY

The utility of temperature cycling as a workmanship screen is recognized by many aerospace companies. The approach to this cycling, however, varies widely from company to company. Table 2 shows the degree of variation in the temperature cycling approaches employed by the 26 aerospace companies and agencies surveyed. The table shows a lack of standardization in employing more than one temperature cycle. It also shows a temperature range between –65 °F and +131 °F (-54 °C to +55°C) to be most commonly used.

Supplier/Agency	No. of Cycles Recommended	Temperature Employed (ºF)	Temperature Range (ºF)
Lockheed Missiles and Space Co.	8 to 10	-20 to 160	180
General Electric Co.	6 to 10	-65 to 131	196
Aerospace Corporation	6 to 8	Variable	-
Decca Radar Ltd.	20	5 to 131	126
Radiation Incorporation	10 to 25	-65 to 131	196
TRW Systems	6	Variable	-
Martin Marietta Aerospace	6 to10	Variable	-
Boeing Co.	3 t o12	-65 to 131	196
Hughes	Variable	Variable	-
Motorola	22	-65 to 160	225
Collins Radio Co.	9 to 25	-65 to 160	225
Honeywell, Incorporated (Denver)	12	-13 to 131	144
Hewlett Packard Co.	16	32 to 131	99
Grumman Aircraft Engineering Co.	4 to 6	Variable	-
Bendix Corporation	6	Variable	-
Delco (AC) Electronics	5	-20 to 120	140
Raytheon – Equipment Div.	5	32 to 160	128
RCA	3	Variable	-
Westinghouse	3 or 4	Variable	-
Sandia Corporation	3 or 5	-65 to 160	225
Texas Instruments	2 to 10	-67 to 131	198
Barnes Engineering Co.	Variable	Variable	-
Goddard Space Flight Center	1	Variable	-
JPL	1	Variable	-
Supplier A	5	-65 o 131	196
Supplier B	1	-65 to 165	230

Table 2. Summary of Temperature Cycles from Survey

2.2.2 NUMBER OF CYCLES AND EQUIPMENT COMPLEXITY

Test and failure rate data provide some interesting insights into the most effective number of temperature cycles to use for workmanship screening. Figure 1 provides a comparative illustration of the number of failures as a function of the number of temperature cycles. Six to ten thermal cycles are required to eliminate most latent workmanship defects.

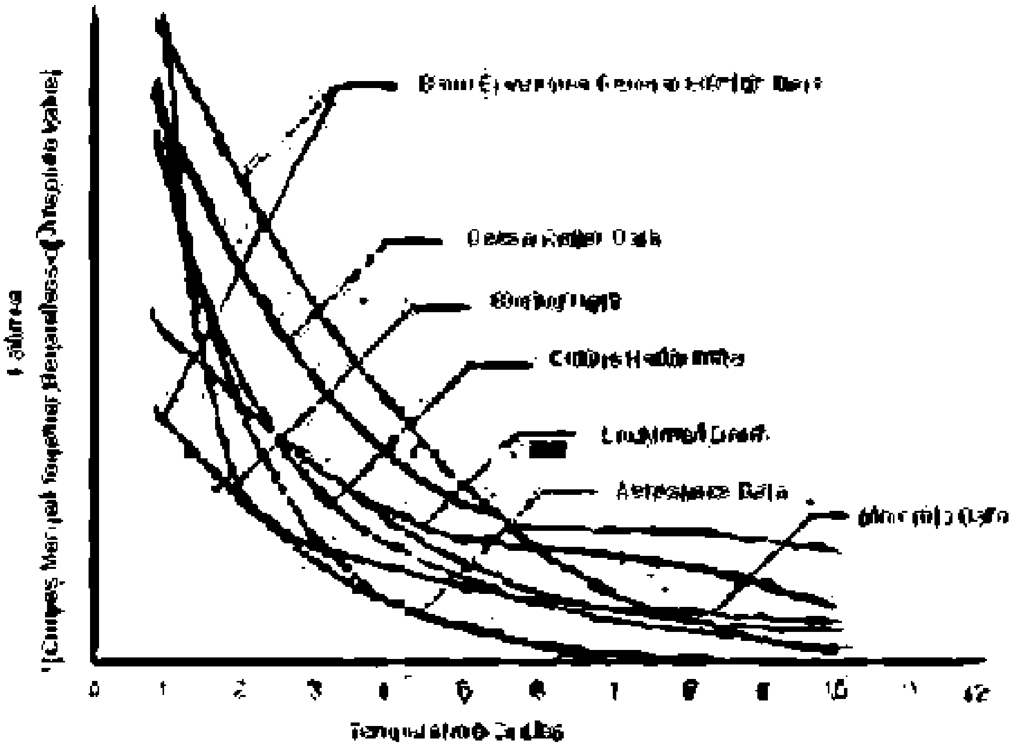

Figure 1. Temperature for Defect Elimination

Investigation of the equipment to which this data applied revealed a useful correlation between equipment complexity and the effective number of temperature cycles required. Six cycles appear adequate for black boxes of about 2000 parts, while 10 cycles are recommended for equipment containing 4000 or more parts, as shown in Figure 2.

Hughes Aircraft Company has developed mathematical models to predict how many cycles are required to achieve a specified reliability. The number depends on the previous amount of screening the quality of parts used, and the exact thermal conditions and profile for the parts being screened. A significant finding is that many more than 10 cycles are sometimes indicated by these models. Similarly, when unscreened parts are used and temperature cycling of assemblies is employed as the main production screen, more than 10 cycles may be required. Programs of 16 to 25 cycles are not unknown.

2.2.3 DURATION OF TEMPERATURE CYCLES

Much of the data in this report is derived from programs using AGREE testing per MIL-STD-781. The AGREE cycle combines temperature ramps, temperature soaks, and low level (29) vibration. The consensus is that the temperature soaks and the low level vibration play a very minor role and, therefore, the AGREE technique is essentially equivalent to a temperature cycling test, with the screening strength of the test dependent on the temperature range, the temperature rate of change, and the number of cycles. The AGREE cycle is shown in Figure 3.

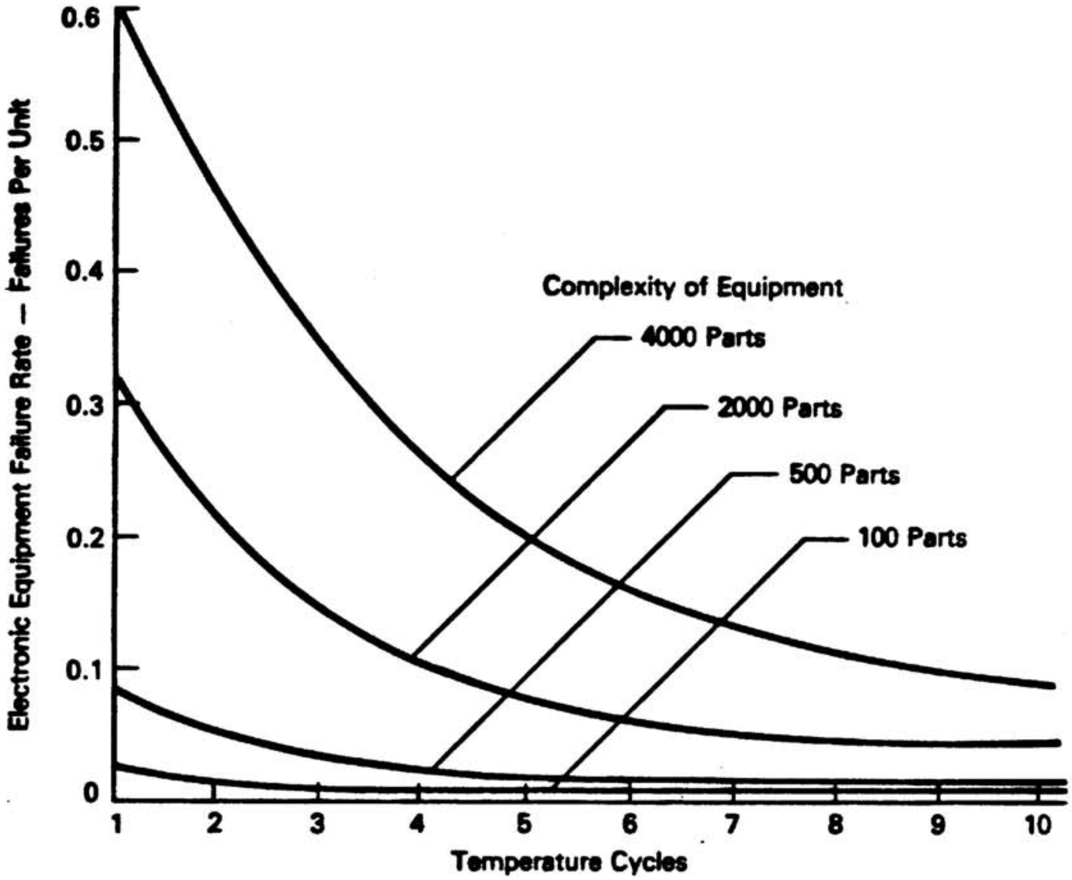

Figure 2. Cycles as a Function of Equipment Complexity

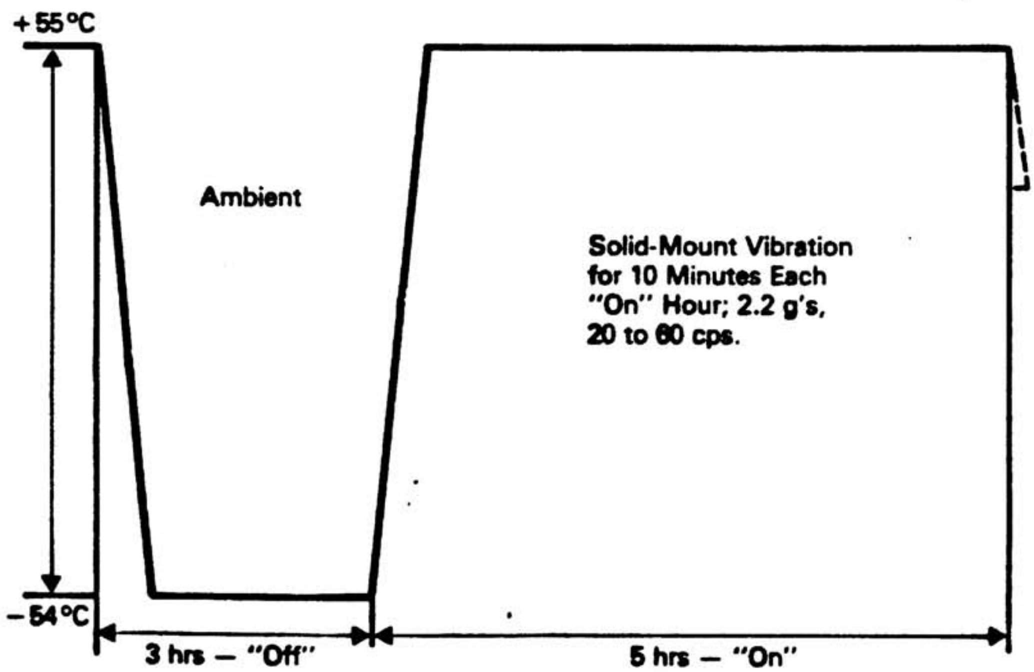

Figure 3. AGREE Environmental Cycle Profile

Accordingly, the dwell times at high and low temperatures need only be long enough for internal temperatures to stabilize, a time which is dependent on the equipment design and which will vary from one program to another. The AGREE cycle in Figure 3 is NOT to be used.

2.2.4 EQUIPMENT OPERATING TIME

The equipment should be closely monitored during the operating portions of the cycle. It is desirable to turn off the equipment during chamber cool-down, otherwise self-generated heat will prevent the internal parts from reaching the desired low temperature.

2.2.5 TEMPERATURE RANGE AND RATE OF CHANGE

Temperature ranges of –65 °F to +131 °F are the temperatures most commonly used. Most parts will withstand temperature cycling with power off through a temperature range of –65 °F to +230 °F. Heat rise with power on under test cooling conditions should be calculated to limit the chamber temperature to a maximum safe value. The maximum safe range of component temperature and the fastest time rate of change of hardware temperatures will provide the best screening. The rate of temperature change of the individual electronic parts depends on the chambers used, the size and mass of the hardware, and whether the equipment covers are taken off. In general, the rate of change of internal parts should fall within 1 °F per minute and 40 °F per minute, with the higher rates providing the best screening.

2.2.6 TEMPERATURE RANGE AND RATE OF CHANGE

Temperature cycling with good parts and packaging techniques is not degrading even with several hundred cycles. However, the packaging design must be compatible with the temperature cycling program or the acceptance test yield will be reduced (to zero in some special cases). This compatibility is established by temperature cycling the pre-production hardware.

Some typical troublesome problems are:

1) Electronic components assembled on printed circuit boards impose loads on the solder joint, and temperature cycling may produce solder joint cracking. Heavy coats of conformal coating on even a stress relief bend can negate the beneficial effect of the bends.
2) Transistors mounted on plastic spacers and coated with conformal coating will produce cracked solder joints in a few temperature cycles if the leads are not stress relieved. This problem arises because the coefficient of thermal expansion for plastics is about 8 to 30 times greater than Kovar transistor leads, or Dumet diode leads.
3) Large multi-pin modules soldered into the printed circuit board may result in solder joint cracking, particularly if the conformal coating bridges between the module and the board.
4) Cordwood modules potted with a rigid, solid polyurethane or epoxy may produce cracked joints and even crush weak parts such as glass diodes on the very first application of a temperature cycle.
5) Filters, motors, and transformers containing fine wire (#40 or #50) may constitute a problem. To avoid the problem, wire sizes larger than #40 should be used.
6) Single or double sided printed circuit boards without plated-through holes are undesirable.
7) Breakage of glass diodes can be expected if great attention is not given to the encapsulating material and the process.

Implementing temperature cycling is most compatible with printed circuit board construction and least compatible with large, complex, potted cordwood modules where failure means scrapping the entire module.

2.2.7 TYPES OF DEFECTS SIMULATED

An approximation of the types of failures detected in mature hardware by temperature cycling is:

Design Marginalities	5%
Workmanship Errors	33%
Faulty Parts	62%

These figures are based on the experience of eight manufacturers as illustrated in Table 3.

Company	Maturity of Hardware	Percent of Failures by Categories		
		Design	Fabrication Workmanship	Parts
General Electric	Immature	33%	33%	34%
	Mature	Approaches 0	10%	90%
Collins	Immature	33%	33%	34%
	Mature	25%	25%	50%
Lockheed	Immature	10%	50%	40%
	Mature			
Motorola	Mature	Approaches 0	10%	90%
Decca	Mature	5%	40%	55%
Martin Marietta	Mature	5%	35%	60%
Boeing	Mature	Approaches 0	50%	50%
Honeywell	Mature	Approaches 0	40%	60%
Averages for Mature Equipment		5%	33%	62%

2.2.8 REPAIRS AND FAILURE-FREE CYCLES

When multiple temperature cycling is used as an acceptance test, it is standard practice to allow repairs without requiring a repeat of the entire test. Some programs have required no failure free cycles, some have required the two final cycles to be failure free, and one program (involving very simple hardware) required 20 consecutive failure free cycles. It is recommended that one final failure free cycle be required, together with criteria for extending the number of temperature cycles as a function of the difficulty and magnitude of the repair.

2.2.9 BOARD LEVEL TEMPERATURE CYCLING

The concept of augmenting the black box temperature cycling with additional cycling at the printed circuit board level should be considered. Hughes Aircraft Company, on one program, "stores" their assembled printed circuit boards in a temperature chamber for one week during which time 158 temperature cycles are accrued. The boards are not powered or monitored. This comprises a very cost-effective approach to reliability.

3.0 RANDOM VIBRATION

3.1 BACKGROUND

Historically, acceptance of electronic equipment was originally limited to a form, fit and function appraisal through visual inspections and a functional "smoke" test conducted under room environments. In 1957 the Advisory Group on Reliability of Electronic Equipment (AGREE), created in 1952 by the Department of Defense Research and Development Board to "monitor and stimulate interest in reliability and recommend measures that would result in more reliable equipment," published its recommendations. These included specific requirements for establishing environmental test profiles to be used during reliability demonstration testing. It was also suggested that these same conditions be utilized for acceptance testing of electronic hardware. Vibration was established as one of the environments and was limited to a sinusoidal excitation of ±2g at a fixed non-resonant frequency between 20 and 60 Hertz. This form of vibration persisted for years and was used, with few exceptions, in the majority of electronics and avionic equipment acceptance tests conducted.

Evolving from the McDonnell Douglas Mercury and Gemini manned spacecraft programs, random vibration was utilized to more effectively screen workmanship defects. The unprecedented success of the Apollo manned space program, attributable in large measure to the intensive test program (Reference 2), generated some new thinking in industry and the military concerning the utilization of effective testing (including random vibration) in achieving reliability requirements. Skeptics still maintained that, while those techniques might work for Apollo whose vehicles were essentially "one shot" devices, they probably would not be effective for hardware (such as aircraft avionics) which had to survive thousands of takeoff, flight, and landing hours. The Grumman Aerospace Corporation decided at this time to investigate the merits of sine and random vibration testing. Intuitively, it appeared that random vibration, which provides simultaneous excitation of many modes in contrast to the single frequency sine test, must be more effective in disclosing manufacturing defects. Dr. John Dreher of Wright-Patterson Air Force Base supported this intuition in his paper (Reference 3) where he stated:

> "While it is true that the associated sine sweeps do excite most of these other resonances, one must consider the short time period spent in any one resonance bandwidth and the fact that many of these resonances aren't excited long enough to peak out. In contrast, the random test excites every resonance for the duration of the test."
>
> It appears, then, that the random test proposed is a less severe but more thorough test."

3.2 FINDINGS

3.2.1 VERIFICATION

The scarcity of random vibration application data prompted Grumman to embark in 1971 upon a laboratory test evaluation structured to directly compare the effectiveness of sinusoidal and random vibration (Reference 4). A technical approach was conceived wherein the time-to-failure of typically occurring defects could be examined under controlled environmental conditions and selected durations. Typical workmanship defects, representing 80% of manufacturing problems found in avionic hardware, were selected from Lunar Module (LM) and aircraft test and field failure data. These defects were simulated in quantities considered sufficient for analysis and were inserted into a typical avionic "black box". The test plan provided for a total of 100 simulated defects to be included in any given test matrix of different levels and durations.

Tests were conducted using sine fixed frequency, sine sweep and random vibration excitations at different levels and for varying periods of time. Figure 4, as an example, depicts the matrix for sine sweep testing. Similar matrices were developed for sine fixed frequency and random vibration tests.

The results clearly indicate that random vibration, at a 0.04 g^2/Hz level (Figure 5), was significantly more effective than either of the sinusoidal tests. Figure 6 compares the effectiveness of the three forms of vibration for two of the most common defect types at levels "typically" used in acceptance testing. The results of this comparison are obvious. Figure 7 compares the "typical" random level with a 5g level for each of the sine-type tests. The results show that even at increased levels, the random vibration is more effective (for a given fault type) than sine fixed frequency or sine sweep. In the Figure 8 comparison, levels of vibration up to and exceeding qualification were used for the sine type of test. Although the sine sweep test was close to the "typical" random test for both failure types, it required durations of approximately one hour at qualification levels (10g) to achieve this type of effectiveness. Testing production hardware at these levels and durations would certainly present a potential fatigue problem and would never be utilized in an acceptance test. The "typical" random vibration spectrum achieved its maximum effectiveness in only 10 minutes of testing.

Test Series 1 – Sine Sweep 5 – 500 – 5 Hz			
	Duration		
Level	Low- 10 Min	Med- 30 Min	High- 60 Min
Low – 1.5 g	•	•	•
Med – 5 g	•	•	•
High – 10 g	•	•	•

Each Test – 100 Faults
(20 of 5 Types)

Figure 4. Typical Test Matrix

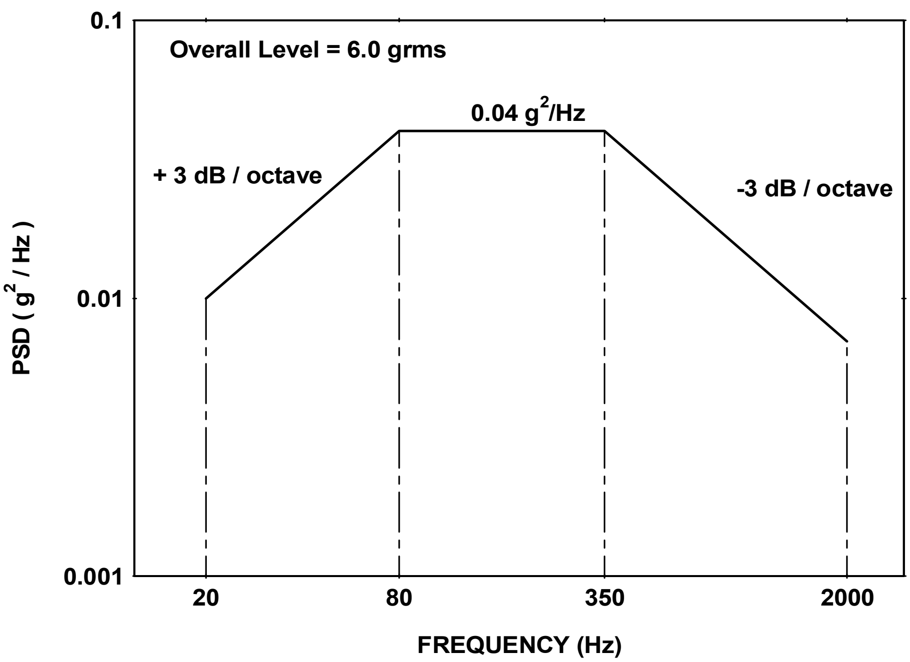

Figure 5. Random Vibration Spectrum

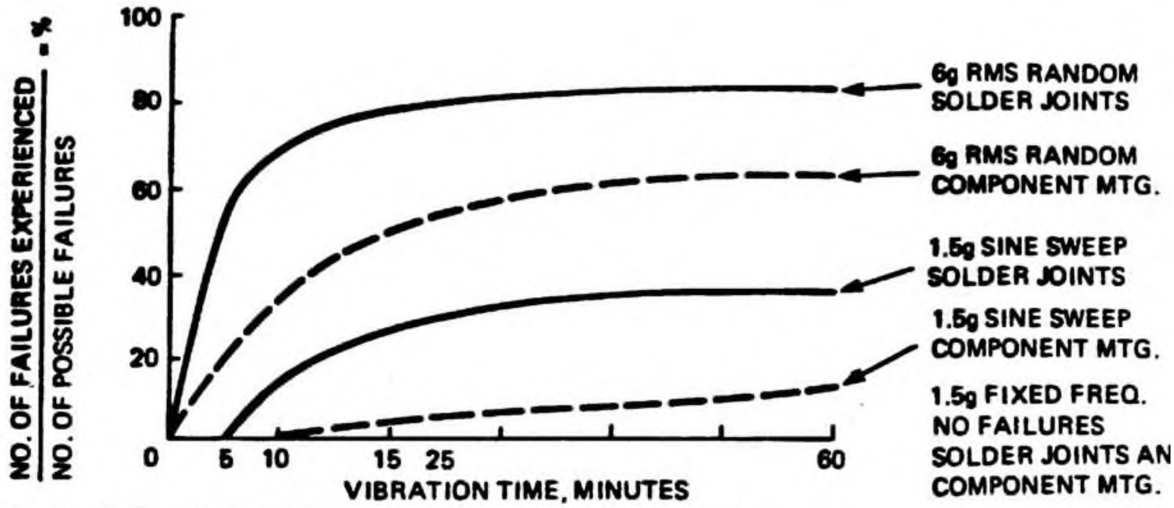

Figure 6. Comparison of Typical Acceptance Test Levels

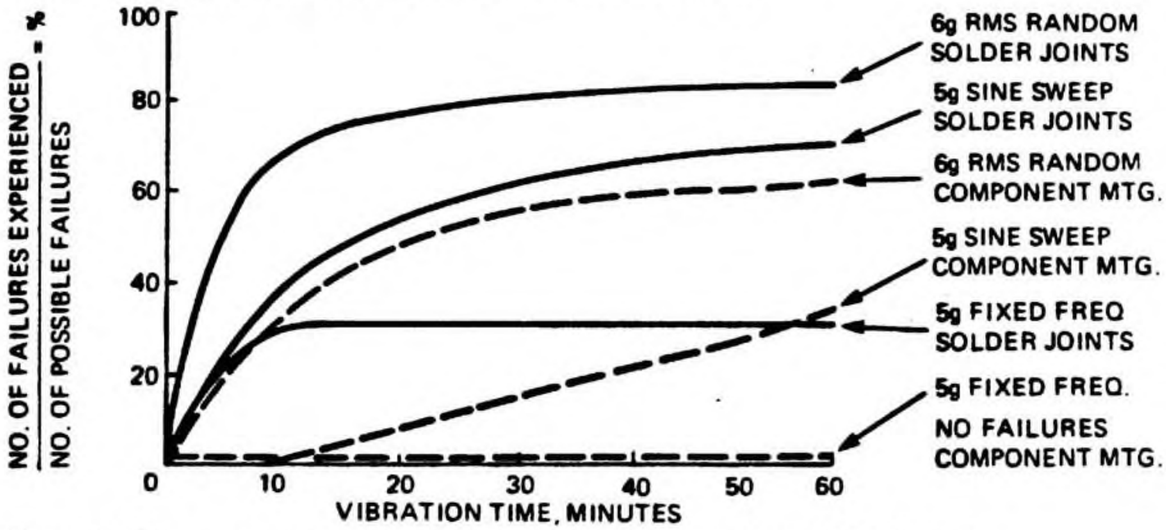

Figure 7. Comparison of Typical Random and Increased Level SS/SF (5 g)

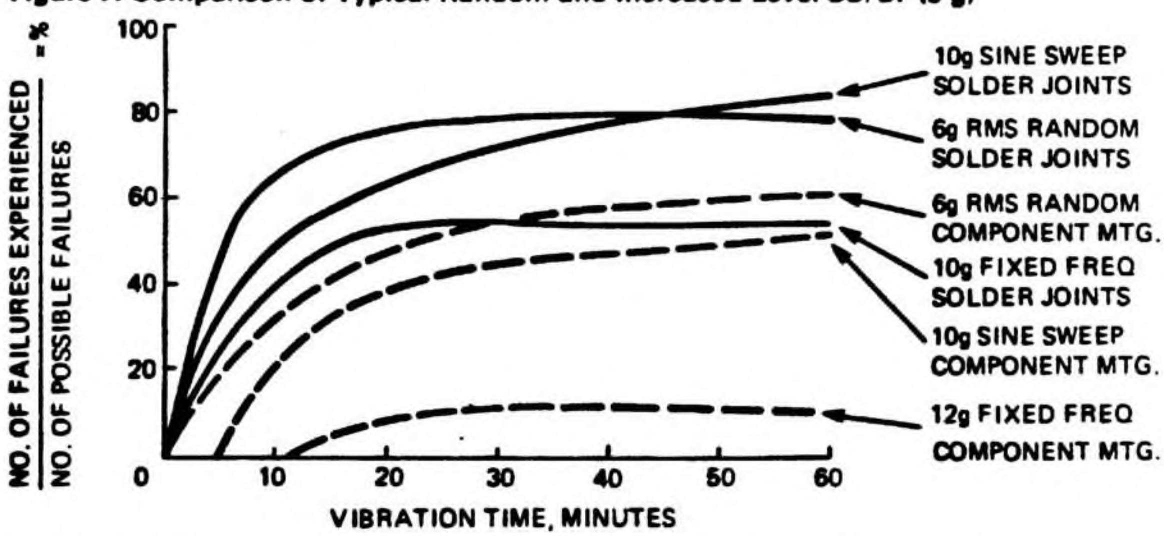

Figure 8. Comparison of Typical Random and Increased Level SS/SF (≥ 10 g)

Some concern has been expressed that the application of a 0.04 g^2/Hz random vibration level would cause fatigue and structural damage if applied to equipment even if that equipment had proven its structural integrity during qualification tests. During the advanced development program conducted by Grumman, a correctly manufactured example of each fault type was inserted in the test article as a control. Even after many hours of exposure at the 0.04 g^2/Hz level, not one of these correctly manufactured examples failed. Further, equivalency analyses performed by Grumman and Wright-Patterson Air Force Base indicate that the 0.04 g^2/Hz level is much less severe than qualification levels currently used. In his paper (Reference 3), Dr. Dreher points out that a fatigue test level of Wf = 0.10 g^2/Hz is equivalent to a sinusoidal level of only Gf = +2.5g. He further indicates that it takes a level of Wf = 1.6 g^2/Hz to be equivalent to a +10g sinusoid. It should be noted that these equivalencies, developed analytically, apply universally to any type of equipment undergoing vibratory excitation.

Additionally, Grumman has had extensive experience in the use of random vibration as an acceptance test, workmanship screen and/or troubleshooting aid. During the LM program over 7,000 tests were performed. In all the history of random vibration applied at this level at Grumman, no known instance of degradation or subsequent field failure attributable to the vibration test has occurred.

3.2.2 APPLICATION

The results of the study conducted by Grumman have had wide distribution. A paper on this subject was presented at the Joint Logistics Commanders' System Reliability Workshop in May 1975. The random form of excitation is now being used by many equipment manufacturers for acceptance purposes. Mr. Wayne Tustin, internationally known vibration lecturer and consultant, strongly endorses its use as an effective workmanship screen (Reference 5). Grumman's initial experience with random vibration was first obtained on the LM program. Following the Advanced Development study efforts described above, the technique was also applied to various avionic equipment installed in Grumman aircraft. The use of random vibration on the LM was originally limited to a level of approximately 39 RMS. In 1967, the NASA informed Grumman that their Gemini experience indicated the level being imposed on LM equipment was not rigorous enough to detect quality/workmanship defects. The level was increased to 6g RMS (currently used - Figure 5) and approximately six months after implementation of the higher level, the effectiveness of the program was assessed. The results indicated that a 3:1 reduction in equipment failures, during spacecraft testing, had been realized.

Application of random vibration to avionic equipment was first accomplished on an airborne computer. After approximately four seconds of random vibration exposure, a malfunction occurred and subsequent analysis revealed several broken solder joints. It is significant that this unit had previously undergone over 100 hours of the "classical" burn-in which included thermal cycling and fixed-frequency sinusoidal vibration. Random vibration has since been applied to many avionic items with a high degree of success. Table 4, typical of the results achieved, shows the delivered MTBF improvement after random vibration was included as part of the acceptance test for these equipments.

Equipment	MTBF W/O RAND VIB (HRS)	MTBF ADDITION OF RAND VIB (HRS)	MTBF IMPROVEMENT
“A”	100-165	250	50 – 150%
“B”	125	380	200%
“C”	58	153	160%

Table 4. MTBF Improvement with Addition of Random Vibration

3.2.3 SYNTHETIC RANDOM VIBRATION

The major deterrent to universal acceptance of random vibration is the impact this type of test would have on program costs since a random vibration test facility is extremely expensive. A concept for economically generating random vibration was evolved which capitalizes on the fact that most major electronic equipment manufacturers maintain basic electrodynamic sinusoidal vibration test facilities. This technique, which was structured to utilize these existing facilities, employs a cassette tape deck, in lieu of expensive random programming devices, to excite the basic shaker system.

The detailed procedures necessary for generating random vibration using an electrodynamic vibration system and a cassette tape deck as a signal source are included herein as an Appendix.

4.0 RECOMMENDATIONS

Manufacturing screening tests of contract end items consisting largely of electronic components should include temperature cycling and random vibration for maximum cost-effectiveness. The purpose of such tests is to stimulate the early occurrence of failures due to manufacturing defects in both parts and workmanship, for discovery and correction prior to delivery to the government. The specific requirements for such tests will be found in Navy instructions and contracts; this publication does not convey policy but is merely the guide to be followed whenever such policy is conveyed.

The tests may be conducted simultaneously or consecutively, depending upon the capabilities of the available test facilities. The equipment under test may or may not be energized and operating depending on considerations, however if not operating a full power on function test should be conducted upon test completion.

4.1 TEMPERATURE CYCLING

The temperature cycling screen should be conducted in accordance with the guidelines shown in Table 5.

Type of Equipment	No. of Temperature Cycles
Simple (100 electronic parts)	1
Moderately complex (500 electronics parts)	3
Complex (2000 electronic parts)	6
Very complex (4000 electronics parts)	10

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Temperature Range

The suggested range is –65 °F to 131°F, or as a minimum, a temperature range of at least 160 °F is recommended.

Temperature Rate of Change

The rate of change of internal parts should fall within 1 °F and 40°F per minute. The higher rates provide the best screening.

Temperature Soak Times

The next temperature ramp may be started when the internal parts have stabilized within 5°F of the specified temperature and the functional checks have been completed.

Equipment Operation

Equipment should be energized and operated during temperature cycling, except the equipment should be turned off during chamber cool-down to permit internal parts to become cold.

Equipment Monitoring

While it is desirable to continuously monitor the equipment during the temperature cycling, cost considerations may dictate otherwise. In such cases, periodic checks plus close monitoring of the final cycles is appropriate.

Failure Criteria

The last cycle shall be failure free. Each repair should be reviewed for the possibilities of introducing new defects into the hardware and additional temperature cycles added when appropriate. If repairs are complex or difficult to make and inspect, or many unscreened parts are used as replacements, additional cycles should be implemented as appropriate to the individual case.

Table 5. Guidelines for Temperature Cycling Acceptance Testing of Electronic Hardware

4.2 RANDOM VIBRATION

The random vibration screen should require that the equipment under test be hard-mounted to a shake table capable of reproducing random vibration having the power spectral density characteristics shown in Figure 5 (repeated herein). A pseudo-random or synthetic random vibration shaker capable of reproducing this power spectral density function will be an acceptable substitute for a true random vibration fixture.

The equipment under test should be oriented on the fixture such that the axis of vibration is perpendicular to the printed circuit boards. Where electronic components in the equipment under test are oriented in more than one plane, such equipment should be shaken sequentially in each of three orthogonal axes.

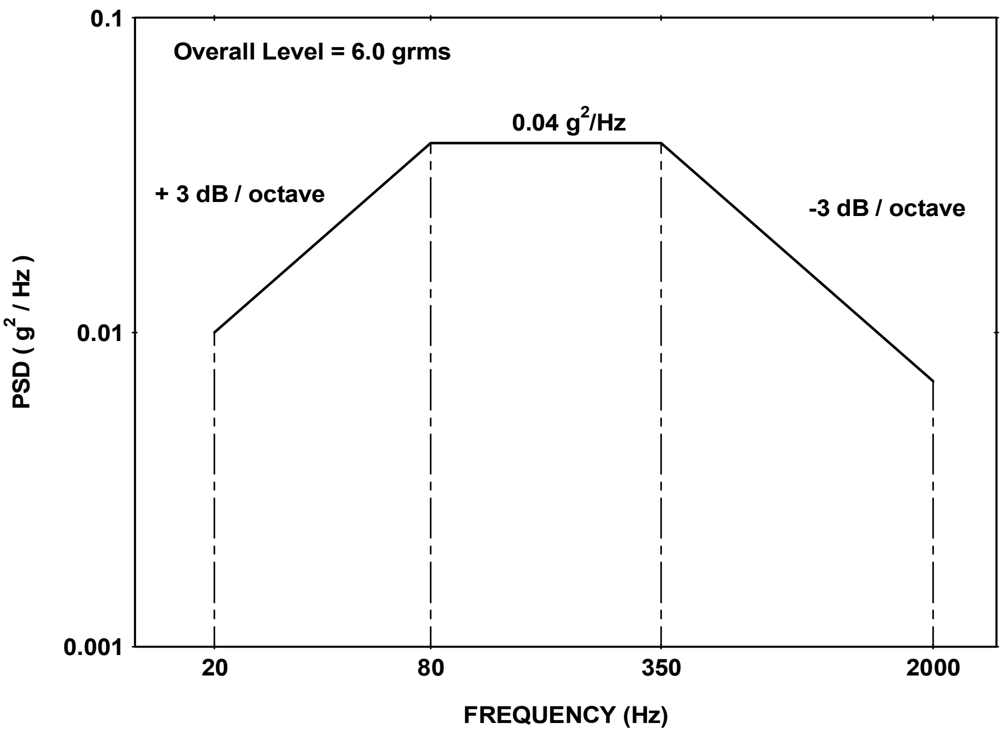

Figure 5. Random Vibration Spectrum

The duration of random vibration should be at least ten minutes if a single axis is sufficient. Where vibration in more than one axis is required, the duration of random vibration should be at least five minutes in each axis.

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