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MILITARY HANDBOOK

ENVIRONMENTAL STRESS SCREENING (ESS) OF ELECTRONIC EQUIPMENT

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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DEPARTMENT OF DEFENSE
WASHINGTON DC 20301

ENVIRONMENTAL STRESS SCREENING (ESS) OF ELECTRONIC EQUIPMENT

1. This standardization handbook was developed by the Department of Defense with the assistance of the military departments, federal agencies, and industry.

2. Every effort has been made to reflect the latest information on Environmental Stress Screening procedures. It is the intent to review this handbook periodically to ensure its completeness and currency.

3. Beneficial comments (recommendatioons, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Commander, Rome Laboratory, AFMC, ATTN: ERSS, Griffiss Air Force Base, New York 13441-4505, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FOREWORD

1. This Handbook provides techniques for planning and evaluating Environmental Stress Screening (ESS) programs. The guidance contained herein departs from other approaches to ESS in that quantitative methods are used to plan and control both the cost and effectiveness of ESS programs. Handbook procedures and methodology were developed under Rome Laboratory contractual and in-house studies. Contractual efforts were performed by the Hughes Aircraft Company of Fullerton, California, under the direction of Mr. A.E. Saari and Litton Systems Canada Limited of Toronto, Ontario under the direction of Mr. R.A. Pepperall. The Handbook includes the guidance contained in R&M 2000 ESS Policy Letter dated 25 Jun 86.

2. Environmental Stress Screening (ESS) programs, which are applied during the development and production phases, can yield significant improvements in field reliability and reductions in field maintenance costs. Application during development can reap significant savings in test time and costs as a result of eliminating or reducing the number of latent defects prior to qualification tests. The benefits for the manufacturer include: a high degree of visibility as to the sources of reliability problems in the product or process, better control of rework costs, and the opportunity to determine corrective actions which eliminate the sources of reliability problems from the product or process.

3. There are various approaches associated with the application of stress screens. Regardless of the approach used, the fundamental objective of ESS remains the same; i.e., to remove latent defects from the product prior to field delivery. The quantitative methods, contained in this Handbook, extend this objective by focusing on the defects which remain in the product at delivery and their impact on field reliability. The goal of ESS programs thus becomes to reduce the latent defect population, at delivery, to a level which is consistent with the reliability requirements for the product. Reduction of the latent defect population in a production lot of electronic equipment, is accomplished by:

a. Use of ESS to precipitate flaws in the assembled hardware to a detectable level coupled with the use of thorough tests to facilitate their detection and removal.

b. Use of ESS results to isolate and defect failure causes followed by determining appropriate corrective actions. Effective corrective actions eliminate the source (cause) of the defect from the process or product, thereby improving manufacturing process capability.

4. General guidelines and supporting rationale in Section 4 and detailed guidelines in Section 5 provide the user with the procedures needed to plan, monitor and control the screening process so that quantitative goals can be achieved cost effectively. The six detailed procedures of Section 5 are entitled:

Procedure A - Optimizing Screen Selection and Placement
Procedure B - Estimating Defect Density
Procedure C - Estimating Screening Strength
Procedure D - Refining Estimates of Defect Density and Screening Strength
Procedure E - Monitor and Control
Procedure F - Product Reliability Verification Test (PRVT).

5. It should be noted that it is not possible to eliminate all defects from the hardware through stress screening. The vast majority of parts in the hardware will never fail throughout the life of the product. However, some fraction of the parts contain gross latent defects and tend to fail early and thus dominate the reliability of fielded products during early life. The objective is to remove as many of the gross defects from the hardware as is technically and economically feasible so as to achieve the designed-in or required reliability. The Handbook implements these objectives through use of controls on the latent defects present in the hardware at assembly, the costs to precipitate and remove them, and the assurance needed that latent defects remaining in the hardware at delivery will allow reliability objectives to be achieved.

6. The procedures provided in the Handbook are an important aspect of a manufacturer's TQM program and philosophy. The procedures quantify some elements of customers satisfaction that are measured by cost and reliability and reflect these as factory goals and requirements that are thus meaningfully and directly related to the customers measures of satisfaction. These factory requirements apply to all levels from the procurement of parts

and materials from vendors through all factory processes and tests and affect both management and design philosophies. The procedures also provide management and working level groups with quantitative feedback on their performance compared with requirements and goals for continuous improvement. If problem areas or deficiencies are identified the procedures help analyze options for defect control or prevention.

7. This revision to MIL-HDBK-344A provides the following changes based upon a recently completed study, reference RL-TR-91-300, Vol. 1, "Evaluation of Quantitative Environmental Stress Screening (ESS) methods. The changes do not affect the basic concepts and methodology of the handbook.

a. Incoming defects per system are calculated in a manner slightly different than the original handbook. The complexity of a system is described by the number of items in various type-reliability grade categories. The defects per system are then calculated by multiplying each of these complexity values by the corresponding defect density for each category. Workmanship complexity and their defects are determined based upon the MIL-STD-2000 assembly and solder complexity numbers. This change was made to improve the accuracy of the estimated workmanship defects. The defect population (i.e. parts and workmanship) is proportioned into separate populations that are sensitive to Random Vibration (RV) and Temperature Cycling (TC) stresses. ESS calculations are subsequently performed on these separate populations. This change was made to improve modeling accuracy and to ensure a proper balance of RV and TC screens. The defects are determined relative to the R&M 2000 stress levels. These stress levels are defined to be the reference or baseline stress levels. Defect densities for other factory ESS stress levels are determined by multiplying the reference values by an appropriate Stress Adjustment Factor (SAF). The values of field defects under different operating environments are calculated using the defect densities for that environment, e.g.. AIF, etc.

b. The calculations of defects removed and defects remaining are also similar to the existing handbook in that the defects removed are calculated by multiplying the system (or assembly) defect density by the applicable screening strength. The recommended changes affect the procedure as follows:

i.) The defects removed by screening are calculated relative to the baseline stress. The actual defects removed are then calculated by multiplying the removals by an appropriate stress adjustment factor.

ii.) The terminology was changed from Test Strength = Screening Strength x Detection Efficiency to Screening Strength = Precipitation Efficiency x Detection Efficiency. This change was made to make the terminology more consistent and descriptive.

iii.) Precipitation efficiency is determined using the same equations as those used to produce values found in previous HDBK tables (DoD-Hdbk-344). The precipitation efficiency for RV however was modified to include an axis sensitivity factor. This change was made to improve modeling accuracy based on the axis sensitivity observed in the study.

iv.) The stress parameters e.g. Grms, Temperature Transition Rate etc. are defined relative to the unit under test and not the environmental chambers. The requirement for thermal and vibration surveys to determine appropriate values was also added. (Consistent with this change, the stress level in the precipitation efficiency equation may need to be rescaled.)

v.) The requirement to calculate the damage factors due to the ESS was added to ensure that the ESS stress levels and duration are not destructive or consume a significant portion of the useful fatigue life.

c. Further changes and refinements concerned the data analysis, Statistical Process Control (SPC) procedures and the requirements for Failure Free Acceptance Test (FFAT).

i.) The procedures were modified to encourage the maximum use of observed data. Initial estimates of defect density and screening strength are made using the HDBK/industry data base; however, these estimates are subsequently refined by the user based on the actual data. The methodology provided to enable the user to measure the ESS parameters (e.g. defect density, screening strength etc.) is based on a curve fitting solution to the general ESS mathematical expression developed in Appendix A. These changes were made to eliminate the need for highly accurate data in the HDBK.

ii.) For analysis and modeling purposes defects are segregated into errors and defects with defects being further subdivided into latent and patent defects. Since it is precipitated latent defects that determine the reliability in the field it is important to distinguish between errors and defects. Although the user must minimize and control errors, the improvements in these areas do not necessarily reduce latent defects nor improve reliability.

iii.) The SPC control charts used for monitoring purposes were modified to show requirements that are based on and directly related to the customer's reliability requirements. In addition, the process mean is determined using regression analysis since the mean is expected to change as a result of corrective actions and continuous improvement. A modified form of PARETO charting is also recommended to help identify problems requiring analysis. The modification to the PARETO is to not only compare on the basis of frequency of occurrence but to relate the frequency to that expected based on the unit's complexity and the ESS predictions.

iv.) The mathematical expression described in Appendix A is used to relate remaining defects (at ESS stress levels) to field reliability. This relationship requires prior knowledge of the average time constant in the field. Alternatively, if the actual stress levels are known, the precipitation efficiency equations can be directly applied. With either method, the original estimates are to be refined based on actual data.

v.) The requirement for a failure free acceptance test (FFAT) was eliminated and replaced with an SPC program to measure and control remaining defects. The FFAT requirement was considered to be potentially damaging and uneconomical and tended to be contrary to ESS and the HDBK philosophy of defect elimination and control. A minimum verification test is used however so that ESS can not be entirely eliminated and tests remain in place to collect SPC data.

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1. INTRODUCTION

1.1 Purpose. This Handbook provides uniform procedures, methods and techniques for planning, monitoring and controlling the cost effectiveness of ESS programs for electronic equipment. It is intended to support the requirements of MIL-STD-785, Task 301, "Environmental Stress Screening" and/or MIL-STD-781, Task 401, "Environmental Stress Screening" and to implement Air Force R&M 2000 ESS recommendations and guidelines.

1.2 Application. The Handbook is intended for use by procuring activities and contractors during development and production. It is not intended that the Handbook procedures and techniques be used in a cookbook fashion. Knowledge of the equipment and the manufacturing process is essential for a properly planned and tailored ESS program. The data base needed for a systematic approach to ESS application is not fully developed. Use of the Handbook by Government procuring agencies and equipment manufacturers will foster the development of an improved and broader data base.

1.3 General. A properly applied ESS program can significantly impact the quality and reliability of electronic products delivered to the Government. ESS is interrelated with the requirements set forth in MIL-Q-9858, MIL-STD-785, MIL-STD-781, and MIL-HDBK-781. Quality Control is a manufacturing function and Reliability Engineering is a design function. Although the Quality and Reliability disciplines are related, in practice, they are conducted as separate programs without common objectives. The Handbook uses the ESS program as a means for integrating Quality Control and Reliability Engineering tasks so as to assure achievement of reliability objectives during manufacture. Supporting software is available from Rome Laboratory that fully automates the detailed manual procedures contained herein.

1.3.1 What Is ESS?. ESS is a process or series of processes in which environmental stimuli, such as rapid thermal cycling and random vibration, are applied to electronic items in order to precipitate latent defects to early failure. An equally important and inseparable aspect of the screening process is the testing which is done as part of the screen, so as to detect and properly identify the defects which have been precipitated to failure. The precipitation and testing process is basically a search for defects. Manufacturing techniques for modern electronic hardware consist of hundreds of individual operations and processes through which defects can be introduced into the product. Many of the defects can be detected without the need for stress screens by use of visual inspections, functional tests and other conventional quality assurance procedures. Such defects are termed errors and are a subset of patent defects. A small percentage of latent defects remain undetected by obvious means and, if not removed in the factory, will eventually manifest as early life failures during product use. The inability to find latent defects by obvious means is a consequence of the increased complexity of modern electronic products and the processes which are used in their manufacture. ESS is the vehicle by which latent defects are accelerated to early failure in the factory. ESS can thus be viewed as an extension of the quality control inspection and testing process.

1.3.2 Organization of the Handbook. The Introduction (Section 1) outlines the purpose of the Handbook and provides general introductory remarks pertaining to the quantitative approach to ESS. Section 2 lists applicable references and Section 3 defines terms and acronyms used. Section 4 contains general guidelines and provides the rationale and background for the detailed guidelines. Section 5 contains the detailed guidelines which are organized according to the sequence of events to be undertaken by the contractor in planning, monitoring and controlling a screening program. The detailed procedures are entitled:

. Procedure A	-	Optimizing Screen Selection and Placement
. Procedure B	-	Estimating Defect Density
. Procedure C	-	Estimating Screening Strength
. Procedure D	-	Refining Estimates of Defect Density and Screening Strength
. Procedure E	-	Monitor and Control
. Procedure F	-	Product Reliability Verification Test

Appendix A contains the mathematical relations and model descriptions used in the Handbook. A review of Appendix A will help the interested reader in gaining a quick understanding of the rationale and methodology of the Handbook. Appendix B provides the mathematical foundation for the Product Reliability Verification Test.

Figure 1.1 shows the sequence of application of the various tasks contained in the Handbook and cross-references them to the applicable procedures of the Handbook.

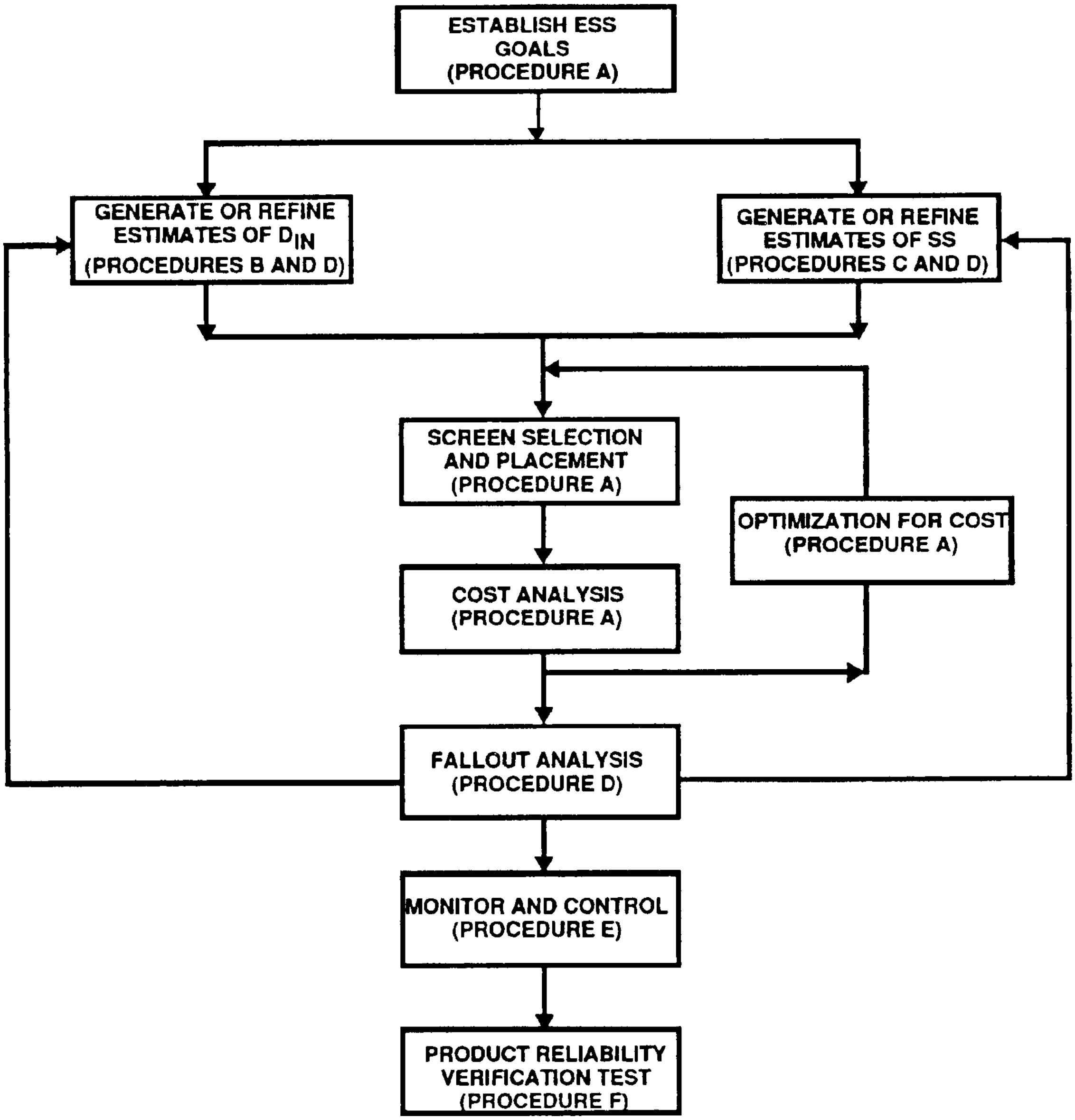
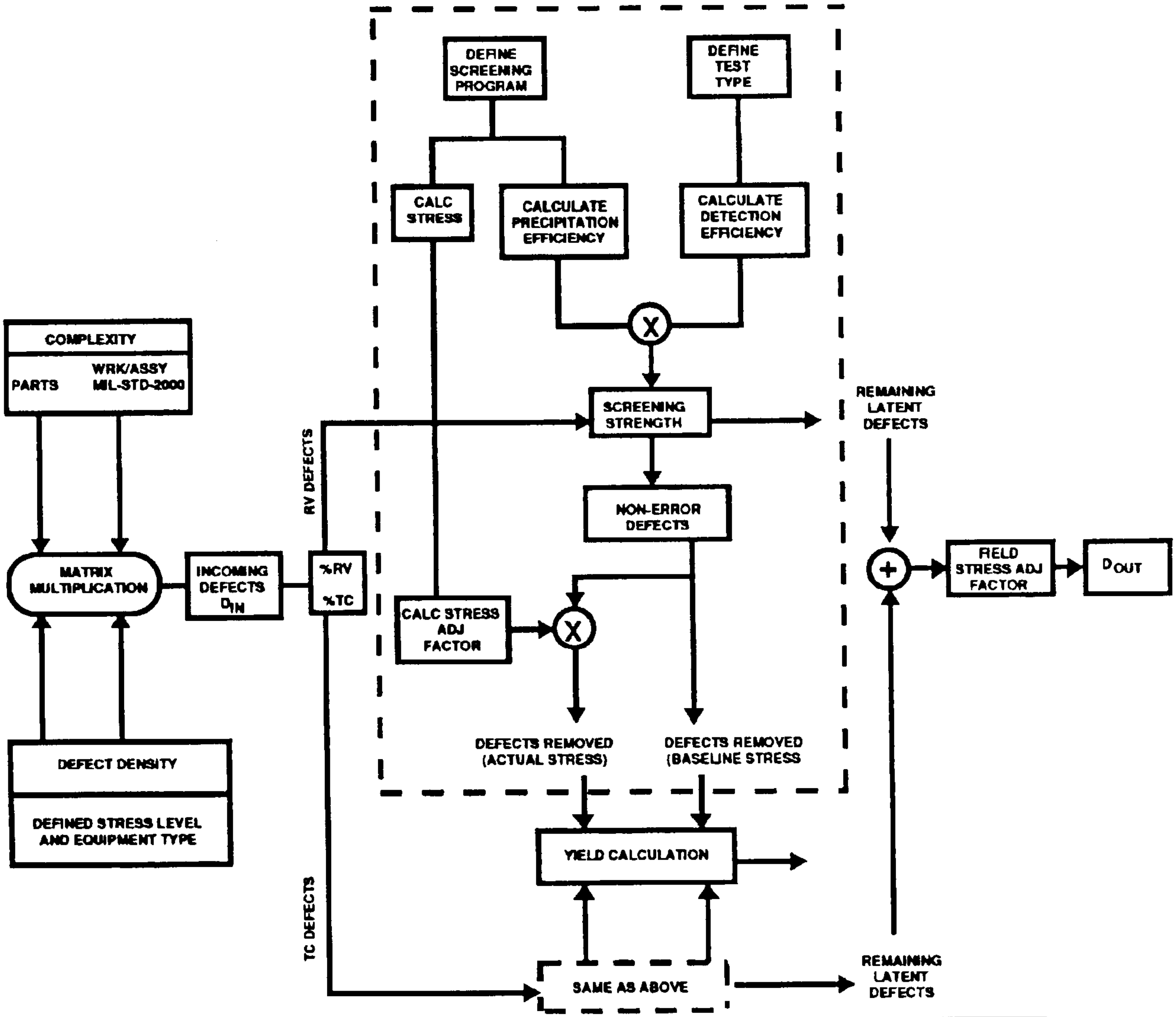


Figure 1.1: Cross Reference of ESS Program Sequence to Handbook Procedures

The product development phase is used to experiment with stress screens to refine the estimate of ESS parameters (D_{IN}, SS) and to define and plan a cost effective screening program for the production phase. The incoming latent defect density is estimated (Procedure B) and screens are selectively placed at various assembly levels to develop a plan for achieving quantitative ESS goals cost-effectively (Procedure A). The ESS plan for the development phase should be submitted as part of the Reliability Program Plan (paragraph 4.4.1).

An ESS plan for the production phase is submitted based upon the experimentation and analyses of cost-effectiveness (Para 4.4.1). After the screening program is implemented during production, the fallout from the screens are used to evaluate the screening process and to establish whether ESS program objectives are being achieved (Procedures D and E). Figure 1.2 shows the detailed mathematical model upon which the ESS program is based. The details will be explained as the reader continues.



The mathematical model can be represented by:

$$D_{REMOVED} = DE \cdot D_{PAT} + DE \cdot D_{LAT}\,[1 - EXP(-kt)] + DE \cdot CFR \cdot t \qquad (A - 9)$$

Where:

DE = Detection Efficiency

D_{PAT} = Patent Defects

D_{LAT} = Latent Defects

k = Stress Constant

t = Stress Duration

CFR = Constant Failure Rate

Figure 1.2: Mathematical Model of an ESS Program

A Product Reliability Verification test is performed and the results used in conjunction with data from the entire factory ESS program to provide assurance that quantitative objectives have been achieved prior to delivery to the customer (Procedure F). The Quantitative goals for the screening program should be established in accordance with the methods outlined in Procedure A.

1.3.3 Development and Production Phase Reliability Assurance. ESS is not a substitute for a sound reliability program conducted during the design and development phases. The inherent reliability of the product is driven primarily by the design. However, without a viable reliability assurance program during production, the reliability which is designed into the product can be seriously degraded. An equipment will eventually pass a MIL-STD-781 reliability demonstration test, either during development or on a sample basis during production. A single equipment passing the MIL-STD-781 test does not imply that all other equipment in the production lot have the same reliability. A relatively few latent defects, contained in various equipment in the lot, can significantly reduce the field reliability, especially for equipment with high reliability requirements. A production reliability assurance program which complements the design/development reliability program, is therefore essential to achieving reliability objectives. A properly planned, monitored and controlled stress screening program, structured as part of a production reliability assurance program, is the vehicle through which product reliability in manufacture can be maintained. The identification and prevention of defect causes through ESS and analysis reduces defect densities for production. This information also provides feedback to a lessons-learned data base to avoid similar deficiencies on subsequent designs or changes. The procedures are oriented toward achieving reliability objectives through use of quantitative methods for stress screening and production reliability assurance.

1.3.4 ESS Application and the Quantitative Approach. Historically there have been two basic approaches to the application of stress screens. In one approach, the Government explicitly specifies the screens and screening parameters to be used at various assembly levels. Failure-free periods are sometimes attached to the screens, as acceptance requirements, in order to provide assurance that the product is reasonably free of defects. Another approach is to have the contractor propose a screening program which is tailored to the product and is subject to the approval of the procuring activity. Although the latter approach is preferred, neither approach is adequate since explicit objectives and the relations between the screening program and quantitative reliability requirements are not always defined. Costs are also uncontrolled because some of the screens might be more efficiently performed, at lower assembly levels, where rework costs are lower. In addition, screening levels may far exceed the design limits of the product and result in damage to the equipment.

There are several unknowns associated with the application of stress screens. How effective are the screens? What is considered acceptable or unacceptable fallout from a screen? How does the quantity of defects remaining in the equipment after delivery to the customer impact field reliability? The aforementioned ESS approaches do not fully address these questions. For example, if the screen fallout is "low", it is not known whether the equipment is "good" (i.e. defect-free) or whether the screen is not effective. On the other hand, if the fallout is "high", it is not known whether the incoming defect levels are inordinately high or whether the screen might be causing non-defectives to fail.

Screens and tests are not perfect. At each stage of manufacture where screens and tests might be applied, from device level to the final system level, escapes to the next assembly stage occur, and new opportunities for introducing defects are created. The number of latent defects which remain in the product at delivery and their impact on field reliability, however, is the primary concern.

1.3.4.1 The Quantitative Approach. The use of a quantitative approach to stress screening requires that the initial part latent defect levels, the defect level introduced during manufacture of the product, the effectiveness of the screens, and reasonably acceptable values for the number of latent defects which remain and escape into the field be addressed. Figures 1.3 and 1.4 illustrate the quantitative aspects of stress screening.

When a quantitative approach to stress screening is used, the key variables of interest are the average number of defects per product which enter the screen (D_{IN} comprised of latent defects (D_{LAT})and patent defects (D_{PAT} and E)), the screen strength (SS) which is the product of Precipitation Efficiency (PE) and Detection Efficiency (DE) and the average number of defects per product which escape the screen/test ($D_{REMAINING}$). Figure 1.4 shows the relationships between these stress screening variables.

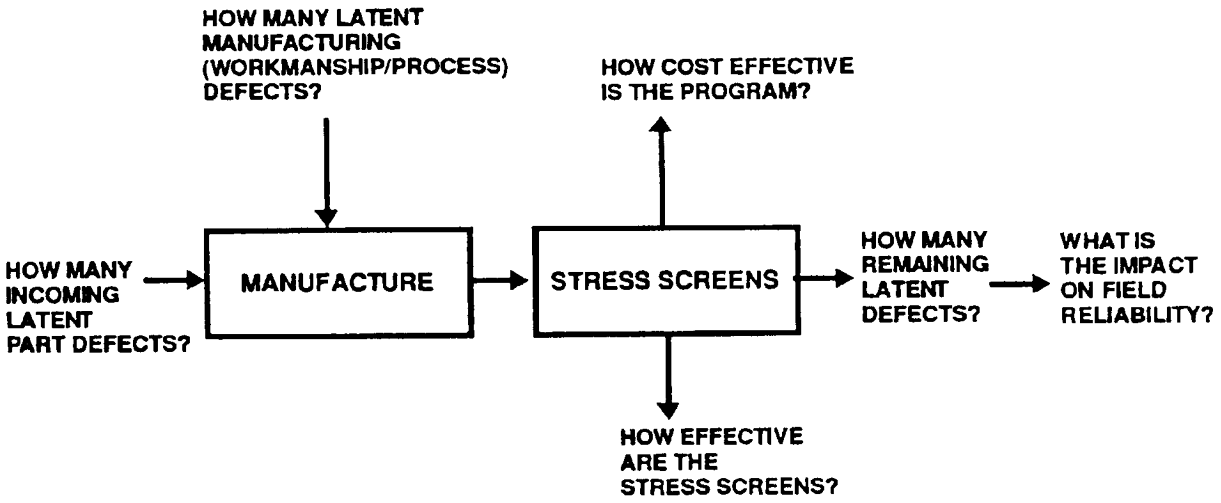


Figure 1.3 : The Quantitative Problem

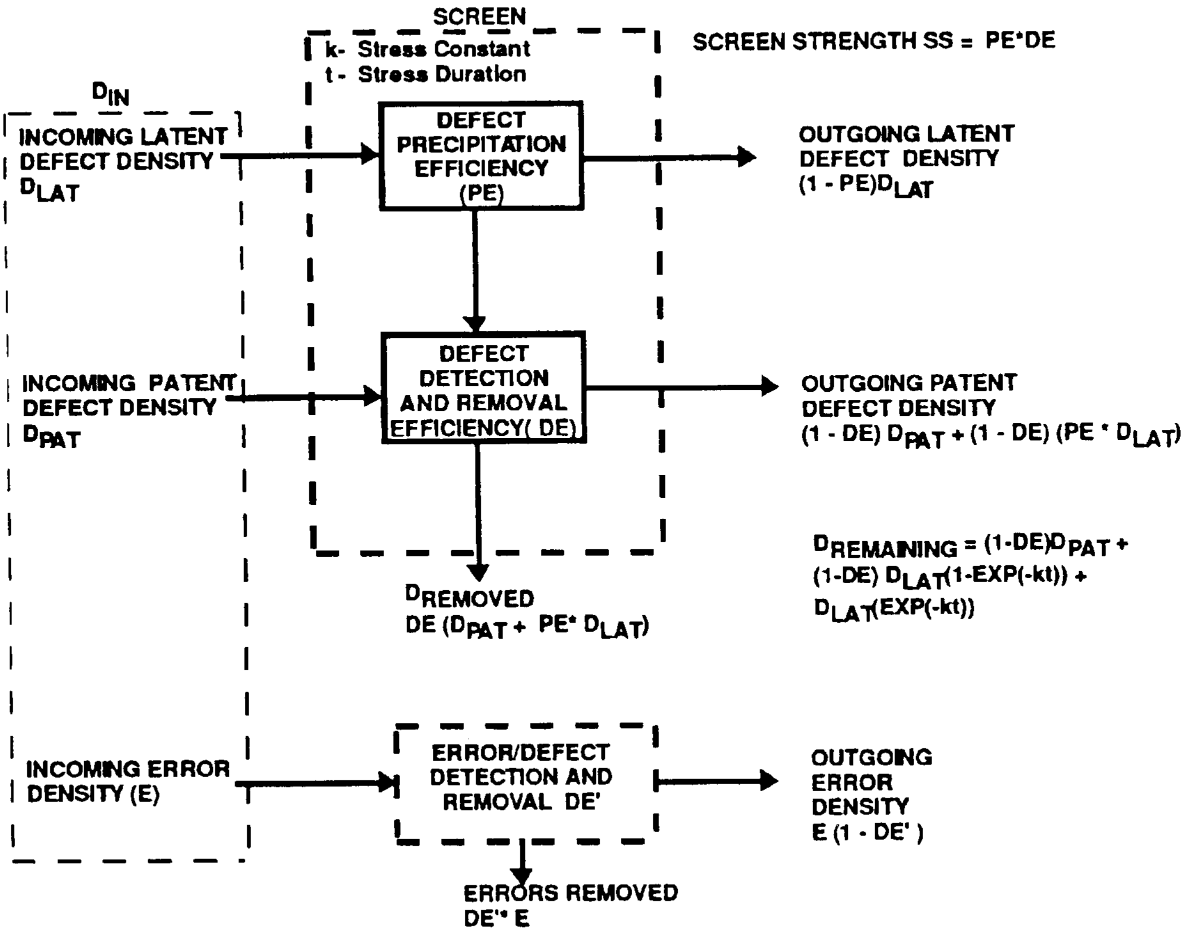


Figure 1.4: Stress Screening and Variable Relationships

The number of defects remaining in the production lot at delivery is a function of three key factors:

a. The quantity of design, part and manufacturing (workmanship and process) defects which initially reside in the hardware prior to assembly level screening.

b. The capability of the environmental stress to precipitate flaws in assemblies to a detectable level.

c. The thoroughness of the testing which is done, either during or after the screen, to assure detection of the defects precipitated to failure by the screens and the ability to fault isolate and remove the defect without introducing new flaws.

None of the three factors which impact the reliability of delivered products is known with certainty. Without a basic knowledge of their quantitative value, however, effective screening programs cannot be properly planned and controlled. The procedures in the handbook are directed at obtaining both preliminary planning and measured estimates of the three factors in order to plan, monitor and control the screening process. Experience data gathered from previous screening programs, screening experiments conducted during the development phase and use of the handbook procedures provides the methodology and information needed to plan and conduct effective screening programs.

Once a screening program is implemented during production, the results must be monitored and appropriate changes made in the screening regimen to assure that goals on remaining defects are achieved. The basic mechanism for assuring control is to compare the screening results with established goals so as to determine the need for corrective actions. For example, corrective actions might be accomplished by increasing precipitation or detection efficiencies so that more defects can be precipitated and detected, or by reducing incoming defect quantities through improved process controls. Changes which reduce or eliminate screening at some levels of assembly can also be taken to reduce costs, when it is found that the screens are ineffective or unnecessary.

1.3.5 Benefits of a Quantitative Approach. A quantitative approach to stress screening enables the establishment of explicit quantitative objectives and provides a basis for planning, monitoring and controlling the screening process to meet those objectives. A quantitative approach also facilitates Government and contractor communication on the status of the screening process and on the progress being made toward achieving objectives. Coupled with a good Failure Reporting Analysis and Corrective Action System (FRACAS), the quantitative approach also provides a more focused emphasis on the sources of latent reliability problems in the product or process as well as better control of costs.

1.3.6 Process Capability and Defect Density. The use of a quantitative approach to stress screening requires addressing the capability of the manufacturing process to produce products which are reasonably free of defects. Defects are introduced into a lot of manufactured products through repeated assembly, handling and testing operations. The average number of defects per product (defect density) varies as a function of the degree of control which is exercised over the manufacturing process and the process capability. The ESS program addresses the questions: What is the process capability? What must the process capability be in order to meet quantitative reliability objectives? What improvements and changes are required to achieve the reliability objectives at optimum cost?

2. REFERENCED DOCUMENTS

The documents cited in this section are for guidance and information.

2.1 Government Documents.

SPECIFICATIONS

MIL-Q-9858	Quality Program Requirements

STANDARDS

MIL-STD-721	Definition of Terms for Reliability and Maintainability
MIL-STD-781	Reliability Testing for Engineering Development, Qualification, And Production
MIL-STD-785	Reliability Program For Systems and Equipment Development and Production
MIL-STD-883	Test Methods and Procedures for Microelectronics
MIL-STD-2000	Standard Requirements for Soldered Electrical and Electronic Assemblies
MIL-STD-2155	Failure Reporting, Analysis And Corrective Action System

HANDBOOKS

MIL-HDBK-217	Reliability Prediction of Electronic Equipment
MIL-HDBK-781	Reliability Test Methods, Plans, and Environments for Engineering Development, Qualification, and Production
MIL-HDBK-338	Electronic Reliability Design Handbook

PUBLICATIONS

Air Force

AFP 800-7	USAF R & M 2000 Process
AFWAL-TR-80-3086	Environmental Burn-In Effectiveness
RADC-TR-82-87	Stress Screening of Electronic Hardware
RADC-TR-86-138	RADC Guide to Environmental Stress Screening
RADC-TR-86-149	Environmental Stress Screening
RADC-TR-87-225	Improved Operational Readiness Through Environmental Stress Screening
RADC-TR-90-269	Quantitative Reliability Growth Factors for Environmental Stress Screening
RL-TR-91-300 Vol I	Evaluation of Quantitative Environmental Stress Screening Methods
RL-TR-91-300 Vol II	DOD-HDBK-344 Software Users Manual

Sacramento Air Logistics Center ESS Handbook

Army

AMC Reg 702-25	Army Material Command Environmental Stress Screening Program

Navy

NAVMAT P-9492	Navy Manufacturing Screening Program
NAVSO-P-6071	Best Practices Handbook
TE000-AB-GTP-020A	Environmental Stress Screening Requirements And Application Manual for Navy Electronic Equipment

DOD

DOD 4245.7-M	Transition From Development To Production
TBD	Tri-Service Environmental Stress Screening Guidelines

Copies of specifications, standards, handbooks, drawings, and publications required by contractors in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the contracting officer. Single copies are also available (without charge) upon written request to:

Standardization Document Order Desk
700 Robins Ave.
Philadelphia PA 19111-5094
(215) 697-2667

2.2 Non Government Documents.

Institute of Environmental Sciences (IES)

Environmental Stress Screening Guidelines, 1981

Environmental Stress Screening Guidelines for Assemblies, Sep 84

Environmental Stress Screening Guidelines for Assemblies, Mar 90

Environmental Stress Screening Guidelines for Parts

(Application for copies should be addressed to the Institute of Environmental Sciences, 940 East Northwest Highway, Mt. Prospect IL 60056-3444)

Electronic Industries Association (EIA)

Interim Standard No. 18 Lot Acceptance Procedure for Verifying Compliance with the Specified Quality Level (SQL) in PPM

(Application for copies should be addressed to the Electronic Industries Association, 2001 Eye Street, NW, Washington DC 20006 5009)

2.2.1 Other Non Government Documents.

Fertig, K.W., Murthy, V.K., "Models for Reliability Growth During Burn-In", Proceedings of the

1978 Annual R&M Symposium, pp. 504-509.

Bateson. J.T., "Board Test Strategies - Production Testing in the Factory of the Future", Test and Measurement World, pp. 118-129, Dec 84.

Kube, F., Hirschberger, G., "An Investigation to Determine Effective Equipment Acceptance Test Methods", Grumman Aerospace Corporation, Report No., ADR 14-04-73, Apr 73

Brownlee, K.A. (1960), Statistical Theory and Methodology in Science and Engineering, New York, John Wiley and Sons

Crandall, Random Vibration, John Wiley and Son

Engelmaier, Effects of Power Cycling in LCC, Bell Laboratories N.J.

Quinn, J.J. "How To Implement DoD-Hdbk-344 For New And Existing Raytheon Environmental Stress Screening (ESS) Programs", June 1991

(Non government documents are generally available for reference from libraries. They are also distributed among non government standards bodies and using Federal agencies.)

3. DEFINITIONS AND ACRONYMS

3.1 <u>Definitions</u>. Definitions applicable to this Handbook are:

Assembly/Module	A number of parts joined together to perform a specific function and capable of disassembly, for example a printed circuit board.. An assembly of parts designed to function in conjunction with similar or different modules when assembled into a unit. (e.g. power supply module, core memory module.)
Baseline Stress	Factory ESS stress levels consistent with R&M 2000 guidelines i.e., 6 G_{rms}, $2^{o}C$/min. Measured at Unit Under Test
Chamber	Cabinet in which hardware is placed in order to apply stress to it.
Defect Density	Average number of latent defects per item. Symbols used: D_{IN}, D_{OUT}, $D_{REMAINING}$ and D_{O} for incoming, outgoing, remaining and observed defect density, respectively.
Detectable Failure	A failure that can be detected with 100% detection efficiency.
Detection Efficiency	A measure of the capability of detecting a patent defect. Symbol is DE.
Error	Class of patent defect resulting from assembly and/or test correlation errors. Errors do not require environmental stress for precipitation or detection.
Escapes	The incoming defect density which is not detected by a screen and test and which is passed on to the next level.
Failure-Free Period	A contiguous period of time during which an item is to operate without the occurrence of a failure while under environmental stress.
Failure Rate	The total number of failures within an item population, divided by the total number of life units expended by that population during a particular measurement interval under stated conditions. Symbol is λ. A reliability measure related to MTBF.
Fallout	Failures observed during, or immediately after, and attributed to stress screens. Symbol is F. Sometimes used to mean defects removed, symbol $D_{REMOVED}$.
Fault Coverage	In a given piece of equipment, the ratio of faults which are detectable to faults present.
Latent Defect	An inherent or induced weakness, not detectable by ordinary means, which will either be precipitated to early failure under environmental stress screening conditions or eventually fail in the intended use environment. Symbol is D_{LAT}.
Part	Any identifiable item within the product which can be removed or repaired (e.g., discrete semiconductor, resistor, IC, solder joint, connector).
Part Fraction Defective	The number of defective parts contained in a part population divided by the total number of parts in the population expressed in Parts Per Million (PPM). See also defect density.

Patent Defect	An inherent or induced weakness which can be detected by inspection, functional test, or other defined means. Symbol is D_{PAT}. In this procedure, D_{PAT} refers to precipitated latent defect. See also error.
Precipitation (of Defects)	The process of transforming a latent defect into a patent defect through the application of stress screens.
Precipitation Efficiency	A measure of the capability of a screen to precipitate latent defects to failure. Symbol is PE.
Production Lot	A group of items manufactured under essentially the same conditions and processes.
Product Reliability Verification Test	A test to provide confidence that field reliability will be achieved.
Screenable Latent Defect	A latent defect which is accelerated to failure by a screen and then detected by test.
Screen Parameters	Parameters which relate to screening strength, (e.g., vibration G-levels, temperature rate of change and time duration).
Screening Experiments	Stress screening applied to preproduction equipment in order to derive data such as screen parameters for planning the overall ESS program.
Screening Regimen	A combination of stress screens applied to an equipment, identified in the order of application (i.e., assembly, unit and system screens).
Screening Strength	The probability that a specific screen will precipitate a latent defect to failure and detect it by test, given that a latent defect susceptible to the screen is present. It is the product of precipitation efficiency and detection efficiency. Symbol is SS.
Selection and Placement	The process of systematically selecting the most effective stress screens and placing them at the appropriate levels of assembly.
Stress Adjustment Factor	The ratio of the incoming defect density at the anticipated field stress level to the incoming defect density at the base line stress level.
Stress Screening	The process of applying mechanical, electrical and/or thermal stresses to an equipment item for the purpose of precipitating latent part and workmanship defects to early failure.
System/Equipment	A group of units interconnected or assembled to perform some overall electronic function (e.g., electronic flight control system, communications system).
Thermal Survey	The measurement of thermal response characteristics at points of interest within an equipment when temperature extremes are applied to the equipment.
Unit	A self-contained collection of parts and/or assemblies within one package performing a specific function or group of functions, and removable as a single package from an operating system (i.e., auto pilot computer, vhf communications, transmitter).
Vibration Survey	The measurement of vibration response characteristics at points of interest within an equipment when vibration excitation is applied to the equipment.

Yield	The probability that an equipment will pass a screen or test without failure.

3.2 Acronyms/Abbreviations

3.2.1 Acronyms Used In Procedure B Of Section 5

Abbreviation	Description
AIC	Airborne Inhabited Cargo
AIF	Airborne Inhabited Fighter
AUC	Airborne Uninhabited Cargo
AUF	Airborne Uninhabited Fighter
ARW	Airborne Rotary Wing
CL	Cannon Launch
GB	Ground Benign
GF	Ground Fixed
GM	Ground Mobile
MF	Missile Flight
ML	Missile Launch
NS	Naval Sheltered
NU	Naval Unsheltered
SF	Space Flight

3.2.2 Other Acronyms

Abbreviation	Description
AOQL	Average Outgoing Quality Limit
ATP	Acceptance Test Procedure
BIT	Built In Test
CDE	Chance Defective Exponential
CFR	Constant Failure Rate
CND	Cannot Duplicate
D	Defect Density
DE	Detection Efficiency
DOD	Department Of Defense
ESD/EOS	Electrostatic Discharge/Electrical Overstress
ESS	Environmental Stress Screening
FBT	Functional Board Tester
FL	Fault Location
FMEA	Failure Mode & Effect Analysis
FR	Failure Rate
FRACAS	Failure Reporting and Corrective Action System
FY	Fiscal Year
HZ	Hertz
IC	Integrated Circuit
ICA	In Circuit Analyzer
ICT	In Circuit Tester
IES	Institute of Environmental Sciences
k	Stress Constant
LBS	Loaded Board Shorts
LRM	Line Replaceable Module
LRU	Line Replaceable Unit
LSI	Large Scale Integration
LTPD	Lot Tolerance Percent Defective
MLE	Maximum Likelihood Estimate

MS	Mechanical Shock
MSI	Medium Scale Integration
MTBF	Mean Time Between Failures
n	Number Of Standard Deviations
N	Sample Or Lot Size
NFF	No Fault Found
OEM	Original Equipment Manufacturer
PE	Precipitation Efficiency
PEP	Production Engineering Phase
PCB	Printed Circuit Board
PPM	Parts Per Million
PRVT	Product Reliability Verification Test
PWA	Printed Wiring Assembly
PM	Performance Monitoring
R	Range
R & M	Reliability & Maintainability
RMS	Root Mean Square
RTOK	Retest OK
RV	Random Vibration
SAF	Stress Adjustment Factor
SRU	Shop Replaceable Unit
SS	Screen Strength
SQL	Specified Quality Level
SPC	Statistical Process Control
t	Stress Duration
TAAF	Test Analyze & Fix
TC	Temperature Cycling
Temp	Temperature
T_{MAX}	Maximum Temperature
TTHB	Time-Temperature-Humidity-Bias
T_{MIN}	Minimum Temperature
TQM	Total Quality Management
UTV	Unable To Verify

4. GENERAL GUIDELINES

4.1 Contractual Aspects of ESS. ESS must remain an adaptive process so that the screening regimen can be changed to improve cost-effectiveness. Contract provisions for ESS programs should have flexibility to effect necessary modifications of stress screens. During the initial stages of production more severe stress screens may be required. As the product and process mature, the screens may require adjustment such as by reducing the number of temperature cycles, the number of axes of vibration or by eliminating unnecessary screens. In early production, a number of unknowns preclude adoption of optimum stress screening. Some of the more significant unknowns are:

a. Residual design deficiencies
b. Manufacturing planning errors
c. Worker training
d. New suppliers
e. Latent defects in new part lots
f. New process capability
g. Precipitation Efficiency
h. Detection Efficiency

The stress screening program, even if carefully planned, may produce unexpected results which should be addressed through modification of the screens, hardware, or processes. The principle of adaptive screening is to adjust the screens on the basis of observed screening results so that the screens are always most cost effective while meeting ESS program goals. Contract terms should be flexible enough to permit modification of screens or screen parameters when such modification can be shown to be beneficial.

In long term production the quantity and distribution of latent defects change with time and therefore contract terms should contain provisions for periodically reassessing the individual screens and the overall screening program. The overriding criterion for change should be the most cost effective achievement of objectives. Contracting arrangements should be made which permit such changes without having to resort to extensive renegotiation.

4.2 Relation of ESS to MIL-STD-785 Reliability Program Tasks. Planning an ESS program for the production phase is interrelated with many of the MIL-STD-785 reliability program tasks which are required to be performed during development and production. Every effort should be made to integrate the knowledge gained from MIL-STD-785 tasks into the planning of an ESS program for production. MIL-STD-785 reliability program tasks which have a particular bearing on ESS planning include: Reliability Prediction (Task 203), Reliability Allocation (Task 202), Qualification Tests (Task 303), Parts Program (Task 207), Failure Reporting Analysis and Corrective Action System (Task 104), Failure Modes, Effects and Criticality Analysis (Task 204), Reliability Growth Testing (Task 302), and of course, ESS (Task 301). Proper screen selection and placement is highly dependent on the reliability and stress design characteristics of the equipment. Information derived from reliability program tasks such as predicted and demonstrated failure rates, quality level of parts, number and type of nonstandard and MIL-parts, number and type of interconnections, design capability, field stress environments, and critical items should be used in structuring an ESS program for production.

4.3 Subcontractor and Supplier Stress Screening. Items which are furnished by subcontractors or other equipment suppliers may require stress screening. There are several distinct advantages for the subcontractor or supplier to perform the stress screening rather than the prime contractor.

a. Subcontractor/supplier concern for yield can be translated to profits which may force process improvements to minimize latent defects.

b. Screening at receiving inspection/test, by the prime contractor, may involve returning defective items to the subcontractor/supplier and result in shortages and schedule slippage's. Performing the additional screen can introduce latent defects due to handling, e.g., mechanical and ESD damage and electrical overstress.

c. Special stress screening facilities and test equipment do not have to be purchased, supported and operated by the prime contractor.

The procedures and methodology contained in the Handbook can be imposed on the subcontractor/supplier. To assure that the subcontractor/supplier is able to perform the tasks required by the Handbook the intent must be made known prior to production. In this manner, the subcontractor/supplier can prepare a screening plan, acquire the necessary capability or arrange for an external laboratory to perform the screening.

4.3.1 Screening of Spares. Spares should be subjected to a screening regimen equivalent to that used for the production hardware. Spares are either manufactured on the same production line or are produced separately to the same specifications as the production hardware. The spares are most often an LRU or SRU and consequently may not receive the exposure to additional screening at higher assembly levels that non-spare items might receive. Quantitative ESS goals for the system should be allocated down to the spare item. The procedures of Section 5 can be used to ensure that defect density for the spares does not exceed allocated goals. A costly and less desirable alternative would be to screen and test all spares in a mock-up configuration for the system. As a word of caution, there are times when spare orders are placed long after the original production run has been completed. As a consequence, the production ESS facilities may not be available. This may lead to a requirement to develop a "new" ESS process that utilizes new/existing facilities. Also given the potential time lag between the actual production phase and the manufacturing of the spares, processes that were in control for production may be out of control for the spares. In such situations it is not recommended to blindly rely on the original production screening regimen.

4.4 Planning a Stress Screening Program. Planning a stress screening program must begin early in the design phase to ensure that the equipment can withstand the necessary ESS stress levels. The success of a stress screening program is strongly dependent on knowledge of the product and the processes to be used in manufacture. The following must be kept in mind when planning a stress screening program using quantitative methods:

a. The defects which can potentially reside in the product and the effectiveness of screens in precipitating the defects to failure (and then detecting them) are not known with certainty. By comparing planned estimates for defect fallout with actual screen fallout, the screening process can be refined and/or the manufacturing process improved to achieve the desired goals of a highly reliable product.

b. Experience data on equipment similar in composition, construction and degree of maturity, can provide very useful data for planning purposes. Information derived from the following sources should be used in planning an ESS program for production:

    (l) Identification of hardware items (parts, assemblies) which have exhibited a high incidence of latent defectives on other programs.

    (2) Identification of suppliers/vendors whose products have indicated high defect levels.

    (3) Qualification test results.

    (4) Supplier acceptance test results.

    (5) Part receiving inspection, test and screening results.

    (6) Screening and test records for previous programs.

    (7) Reliability growth test results.

    (8) Field failure data.

c. A viable screening program must be dynamic, i.e. the screening process must be continuously monitored to ensure that it is both technically and cost effective. Changes to the screening process should be made, as necessary, based on analysis of screening fallout data and failure analysis so that quantitative screening objectives can be achieved.

d. The basic questions which must be addressed in planning a stress screening program are:

(1) What are the quantitative objectives of the programs?

(2) What are the stress screens to be used and at what level of assembly should the screens be placed to achieve the desired objectives?

(3) What are the costs associated with each of the possible alternative screening sequences and how can the screening program be made cost effective?

(4) How will one know if the screening program is proceeding according to plan? What assurances can be provided that program objectives have been achieved?

(5) What corrective actions must be taken to achieve desired screening program goals if the screening fallout data indicate significant departures from the planned program?

e. An ESS program for the production phase should include the following major tasks:

(1) Preparation of ESS Plan

(2) Establish Objectives/Goals

(3) Obtain Planning Estimates of Defect Density

(4) Selection and Placement of Screens to Optimize Cost

A discussion of each of these major tasks which includes background, rationale and general guidelines for use of the detailed procedures is contained in 4.4.1 through 4.4.5.

4.4.1 Preparation of ESS Plans. The contractor should prepare ESS plans for both the development and production phases. The purpose of the development phase plan is to describe the proposed application of ESS during development and production and to refine the estimated values of D_{IN} and SS. Use of the procedures contained in the Handbook in conjunction with stress screen experimentation on pre-production prototype equipment (if cost effective) can provide invaluable data for planning. Estimates of the type and quantity of defects likely to be present in the hardware can be evaluated against experimental data. Screens can be designed, based upon engineering evaluation, which provide the desired stress stimulation for suspected defects in the hardware. Test specifications can also be evaluated to ensure that possible failure modes, arising from various defect types and sources, can be detected by the tests performed either during or following the screens. Integration of the results from the MIL-STD-785 reliability program tasks can also be effectively accomplished. Early fallout from screens provides the maximum amount of information on likely defect sources, process capability, and design limitations. Corrective actions taken as a result of screen experimentation during development can aid significantly in stabilizing the process for production. The development phase and production phase ESS plans should be submitted for approval by the procuring activity prior to production.

4.4.1.1 Development Phase Plan. The development phase plan should include the following:

a. Identification of the reliability requirements for the product and the quantitative goals for the ESS program.

b. Identification of the equipment to be screened and the respective production quantities.

c. Description of the initial screens which will be applied and the screening experiments which will be conducted (If experimentation is necessary and cost effective.).

d. Description of the data collection and analysis program which will be used. A Failure

Reporting, Analysis And Corrective Action System (FRACAS) should be in place and operating.

e. Description of subcontractor and supplier stress screening to be performed.

f. Results of preliminary use of the handbook procedures.

g. Identification of the organization elements that will be responsible for ESS planning and experimentation, and the conduct of development phase screening activity.

4.4.1.2 **Production Phase Plan**. The production phase plan should include the following:

a. Quantitative objectives of the ESS program.

b. Detailed breakdown to the assembly level of the equipment which will be screened.

c. Description of the screens which will be applied, including screen parameters and exposure time.

d. Description of the results in applying Procedures A through E of Section 5 including the rationale for achieving quantitative objectives in a cost effective manner.

e. Description of the FRACAS and the analysis procedures which will be used to evaluate and control the screening process.

f. Description of the PRVT to be performed to verify achievement of objectives.

g. Identification of the organizational elements responsible for conducting and evaluating the effectiveness of the production ESS program.

4.4.2 **Establishing Objectives/Goals**. Expressed quantitatively, the objective of a stress screening program is to reduce the incoming latent defect density in a production lot of equipment to an acceptable remaining latent defect density in a cost effective manner. Equipment having high reliability requirements will have more stringent goals on remaining defect density. Methods for determining goals on remaining defect density are discussed in Appendix A. The remaining latent and patent defects determine the field reliability according to the following expression:

$$\text{Average Failure Rate in Field} = \frac{\text{Total failures in time } T}{T} = \frac{1}{MTBF}$$

$$= \text{summation of } \{(1-DE)D_{PAT} + (1-DE)D_{LAT}*SAF*[1-\exp(-kT)] + CFR*T\}/T \text{ for all environments}$$

where:

DE = Detection Efficiency
$(1-DE)D_{PAT}$ = remaining patent defects
$(1-DE)D_{LAT}$ = remaining latent defects
SAF = Stress Adjustment Factor
k = precipitation stress constant

Using this relationship, the required field failure rate can be used to determine the requirements for remaining defect density and consequently used to establish goals and requirements for all integration and test levels from incoming defect densities for parts through to final equipment testing.

An example relating various values of $D_{REMAINING}$ to the field MTBF is shown in Table 4.1 for an assumed field precipitation rate $k = \frac{1}{1000Hr}$.

4.4.3 **Obtaining Planning Estimates of Defect Density**. The design of a stress screening program requires knowledge of the quantity and type of latent defects which are likely to reside in the hardware prior to assembly level screening. The defect density tables contained in Procedure B of Section 5 are used to obtain planning estimates of defect density. Values in the tables are based upon studies of historical defect data from the factory and field for several part types. Extrapolations to other part types and field environments were made based upon correlations to MIL-HDBK-217 quality level and field environment factors. Study results and methodology are contained in RADC-TR-86-149. Procedure D provides the methodology that allows the user to refine these estimates based on experience data.

Table 4.1 Remaining Defect Density Goals (DREMAINING)

Failure Rate (Failures/Hour)	MTBF(Hrs)	DREMAINING (At Field Stress)
0.009516	105	10
0.000951	1,051	1
0.000475	2,102	0.5
0.000190	5,254	0.2
0.000095	10,508	0.1
0.000047	21,017	0.05
0.000019	52,542	0.02
0.000009	105,083	0.01
0.000000	1,050,833	0.001

4.4.3.1 **Latent vs Patent Defects**. A common understanding of the nature of the defects which the screening program should be designed to precipitate is essential for proper planning. The factors which impact incoming defect density and the rationale for the procedures used in obtaining planning estimates of defect density should also be understood.

For ESS purposes defects can be categorized into two types, latent and patent. A latent defect is characterized as an inherent or induced weakness or flaw with some residual strength that will manifest itself as a failure at some time in the future when exposed to normally encountered stress (electrical, mechanical, thermal, or chemical). Latent defects can not be detected until precipitated as a patent defect. For simplicity, a defect with no residual strength but requiring stress concurrent with testing to be detectable can also be considered to be a latent defect until it is detected. Some examples of latent defects are:

(1) Parts
    (a) Partial damage through electrical overstress or electrostatic discharge
    (b) Partial physical damage during handling
    (c) Material or process induced hidden flaws
    (d) Damage inflicted during soldering operations (excessive heat)

(2) Interconnections
    (a) Cold solder joint
    (b) Inadequate/excessive solder
    (c) Broken wire strands
    (d) Insulation damage
    (e) Loose screw termination
    (f) Improper crimp
    (g) Unseated connector contact
    (h) Cracked etch
    (i) Poor contact termination
    (j) Inadequate wire stress relief

A patent defect is a defect that is detectable in its present form and has two subcategories, error and precipitated latent. An error is a defect caused by workmanship or test correlation. Errors are preventable and should not occur, whereas patent defects due to precipitated latent defects are only preventable to the limits of the state of the art in equipment and technology. Errors can be readily monitored using conventional SPC techniques and can be removed by simple testing or inspection without the need for ESS or environmental stress.

Errors are introduced into the product during fabrication, and assembly, and pass through various assembly stages until they are detected by a test or inspection of sufficient thoroughness and subsequently eliminated from the product. When good quality control test and inspection procedures are applied, all but the most subtle errors should be detected and eliminated prior to shipment. Some examples of errors are:

(1) Parts
  (a) Broken or damaged in handling
  (b) Wrong part installed
  (c) Correct part installed incorrectly
  (d) Missing parts
  (e) Electrical test correlation and tolerancing

(2) Interconnections
  (a) Incorrect wire termination
  (b) Open wire due to handling damage
  (c) Wire short to ground due to misrouting or insulation damage
  (d) Missing wire
  (e) Open etch on printed wiring board
  (f) Open plated - through hole
  (g) Shorted etch
  (h) Solder bridge
  (i) Loose wire strand

A precipitated latent defect is a latent flaw that has been transformed into a patent defect by exposure to stress over time. Since detection efficiency is not 100%, some precipitated latent flaws, and errors, will escape to the field as undetected defects. It is thus important to address the aspects of precipitation and detection separately, and also to distinguish and separately monitor errors and precipitated latent flaws. For simplicity the Handbook shall use the term patent defect to define a precipitated latent defect.

4.4.3.2 Categories of Defects. The majority of parts and connections within an electronic equipment will never fail over the product's lifetime and are thus "good". The failures which occur during product life are traceable to design or externally induced causes, or to latent defects which were introduced into the product during manufacture. Such defects, if not eliminated from the product in the factory, will result in premature or early-life failures in the field. Not all latent defects however, are screenable i.e., capable of being eliminated from the equipment in the factory by use of stress screens. It is only those latent defects, whose failure threshold can be accelerated by the stresses imposed by the screens, which are screenable. It is the screenable early life failure which the stress screening program must be designed to remove. Figure 4.1 illustrates the categories of defects and their relationship to product life failures.

4.4.3.2.1 Screenable Latent Defects and the Field Stress Environment. The notion of screenable latent defects must be further examined to fully understand the rationale used for the procedures contained in the handbook. The population of latent defects within newly manufactured electronic items can be viewed as a continuum which ranges from minor defects of small size to major defects of large size.

However, it is important to note a somewhat controversial point, i.e., given the same manufacturing process, the number of latent defects which may reside in the hardware will differ, depending upon the operating environment and stress levels to which the equipment will be exposed. The stress/time to which a latent defect is exposed will determine its failure threshold and time-to-failure. The probability of a latent defect's failure threshold being exceeded is much higher in a harsh environment than in a more benign environment.

Obtaining an initial estimate of defect density for an equipment must take into consideration the field operating environment to which the equipment will be exposed during product life.

Since the operating environmental stress levels are different and less than the factory ESS levels, the field defect density estimate is not directly applicable to the factory ESS program. Further, the producer must design, assess, and monitor the ESS program based upon analysis of factory fallout data and causes. Some method must thus be provided to relate defect density in the field to the factory defect density. This is accomplished by including a stress adjustment factor (SAF) in the model, where

$$\text{STRESS ADJUSTMENT FACTOR (SAF)} = \frac{\text{DEFECT DENSITY (FIELD STRESS)}}{\text{DEFECT DENSITY (FACTORY STRESS)}}$$

The application and measurement of the SAF is described in Procedures B and E respectively of section 5.

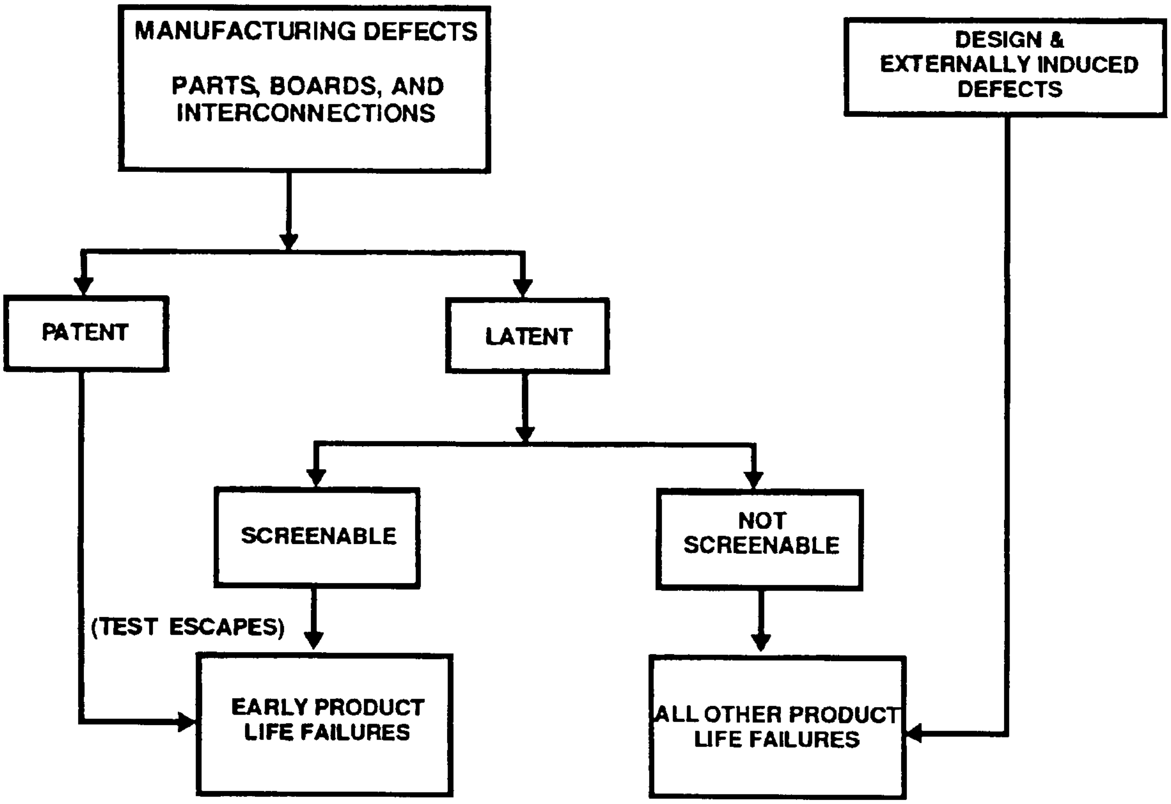


Figure 4.1: Defect Categories & Product Life Failures

4.4.3.3 Factors Which Impact Defect Density. The quantity and type of defects which are introduced into a product are dependent upon several factors. The first six factors, listed below, are related to product or program characteristics for which the manufacturing function within a company has little control. The last two factors are related to the manufacturing process for which the manufacturing function has direct control.

a. Complexity - The quantity and type of parts and interconnections used in the product affects defect density. Increased complexity creates more opportunities for defects.

b. Part Quality Level/Grade - The quality levels of parts are established by MIL-STD part screening requirements. The number of defects which remain in a lot of screened parts is determined by the type and extent of screening and testing to which the parts are subjected under MIL-STD screening requirements.

c. Stress Environment - The stress conditions to which the equipment will be exposed will affect the proportion of defects which should be screened from the product. A defect may be precipitated to early failure in a harsh field operating environment, but may survive product life in a benign field environment.

d. Process Maturity - New production requires time to identify and correct planning and process problems, train personnel and to establish vendor and process controls. Maturity is dependent on volume and time. Low production volume over a long period would have a low maturity rate and will thus impact defect density.

e. Packaging Density - Electronic assemblies with high part and wiring density are more susceptible to process, workmanship and temperature induced defects due to smaller error margins, increased rework difficulty and thermal control problems.

f. Concurrent Engineering - Proper design analysis and assessment and application of Concurrent Engineering principles during the design stage will tend to ensure a reliable and producible product and thus reduce the latent (and error) defect densities. Durability analyses will also ensure that the design can withstand the stresses of ESS.

The following factors are under the direct control of the manufacturing function. The degree of control exercised will impact defect density.

g. Manufacturing Process Controls - Good process controls will tend to reduce the number of defects which are introduced into the product.

h. Workmanship Quality Standards - Stringent and properly enforced workmanship quality standards will enhance the reliability of the product through reduced introduction of workmanship defects into the product.

4.4.3.3.1 Part vs Assembly Defect Density. The part defect density can have a significant impact on the assembly defect density depending upon the number of parts contained in the assembly. The Poisson approximation is used in Figure 4.2 to illustrate the expected assembly defect density as a function of the remaining part defect density and the number of parts per assembly. As can be noted relatively small values of part defect density result in large values of assembly defect density depending upon the number of parts contained in the assembly. As an example, for a 150 part assembly containing parts with a Defect density of .01 (10,000 PPM), the assembly defect density is 1.5. In terms of yield, only about 22% i.e. exp(-1.5) of such assemblies, when subjected to first assembly test, would pass without failure. It is quite obvious that the part defect density must be much better than .01 if the costs of rework, retesting and handling of the assemblies are to be avoided. The questions answered by the ESS methodology and procedures in this handbook are: How much better must the remaining part defect density be? What level of part defect density is needed for delivered systems? Can such levels be achieved?

4.4.3.3.2 Part Level vs Assembly Level Screening. Screening at the part level may be a cost effective alternative for eliminating defects prior to the parts being assembled into the production hardware. A population of parts, even those procured to high quality levels, may appear to contain high defect density levels. For example, microelectronic devices procured to the quality requirements of MIL-STD-883 receive 100% final electrical testing by the part vendor. Nonetheless, one manufacturer has found that about 1%, and as much as 4% of the parts will not pass a similar electrical test performed at the OEM receiving inspection. There are several possible reasons for this including:

- the seller's and buyer's tests are different
- seller testing errors
- buyer testing errors
- device damage or degradation in handling
- inspection and sorting errors.
- latent defects

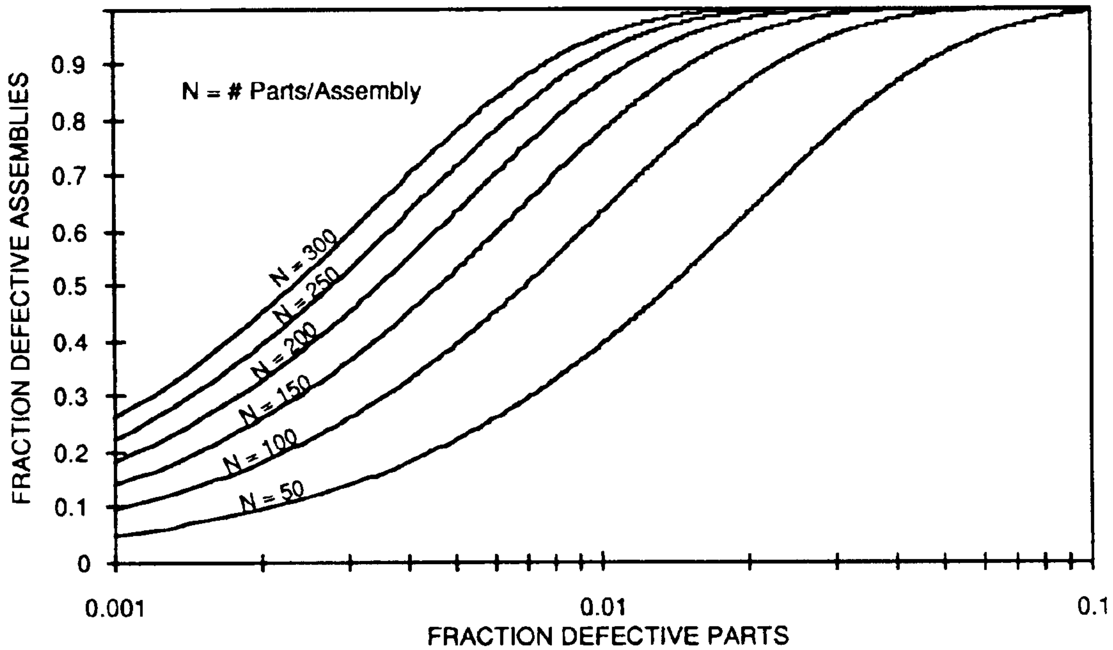


Figure 4.2: Fraction Of Defective Assemblies Vs Remaining Part Fraction Defective

General awareness of this problem in industry has resulted in improvements in part quality and reliability. For example, results reported in the Integrated Circuit Screening Report published by the IES in November, 1988 indicated a significant improvement for microcircuits and revealed that the additional handling involved in the rescreening process was actually introducing more defects that were being screened.

None the less, it should be noted that the foregoing discussion addresses errors only and must be extended to include latent defects and that it is primarily latent defects that escape to the field and degrade early life reliability.

The requirement for parts rescreening should not be mandated and should only be used as determined to be necessary by the implementation of the Handbook.

Screening at the assembly level is also a means of finding and eliminating part defects from the hardware. The part fallout from early screening at the assembly level can provide much of the information needed for resolving such uncertainties and taking corrective action. There are always uncertainties as to whether the part defects which are found during assembly level screening, are escapes from part level screens or whether they are newly introduced defects due to handling, test and assembly operations. A thorough failure analysis of the fallout from assembly level screening can help in determining defect causes and the types of screens which should be used.

4.4.3.3.3 Air Force R&M 2000 ESS Policy-Part Fraction Defective. Air Force R&M 2000 ESS studies recommend that the manufacturing process begin with piece parts having a remaining part fraction defective below 1000 PPM by FY87 and below 100 PPM by FY90. Procedure D of Section 5 and ESS results are used in the Handbook procedures to evaluate the achievement of these goals. However, the prescribed requirement of 100 PPM defect level for parts may not be adequate for achieving the required reliability. The actual requirements should be determined using Procedure A and may increase or relax the R&M 2000 levels. The R&M 2000 levels should also be interpreted as being applicable to both latent and patent defects where the patent defects include errors due to electrical testing, test correlation, specification discrepancies etc.

4.4.3.3.4 Process Maturity and Defects. The maturity of both the product design and the manufacturing process can significantly impact the quantity and type of defects which can reside in the hardware. The data shown in Table 4.2 represent experience on several large development and production projects. As the data illustrate, the proportions of failures in a product which are traceable to design, part or manufacturing causes can differ substantially, depending upon the stage of maturity of the product and the manufacturing process. During the development phase, the major contributor to product failure is design (50%), while parts may account for 20% of the failures. Unfortunately, design problems can still be present in the product when stress screens are being conducted during production.

The proportion of failures in a product, attributable to design, would be expected to decrease as the process matures. The overall defect density in the product would also be expected to decrease as the process matures. Maturity of the product and process should be taken into account when planning estimates of defect density are being determined in accordance with Procedure B of Section 5. In such cases, the user may decide to use Procedure D to modify the defect density values in Tables 5.2 through 5.13, of Procedure B either upward or downward, depending upon past experience and assessments of maturity. With an emphasis on TQM and concurrent engineering, more thorough design analysis and assessment should be performed during the design stage to prevent design problems during production. A high incidence of design problems during initial production provides valuable feedback on the efficacy of the concurrent engineering program.

Table 4.2: Defect Types & Density vs Process Maturity

Maturity	Defect Type Distribution (percent)			Defect Density
	Design	Manufacturing	Parts	
Development	40-60	20-40	10-30	High
Early Production	20-40	30-50	20-40	Moderate
Late Production	5-15	20-30	60-70	Low

4.4.3.3.5 Packaging Density. Assemblies with high part and wiring density relative to the assembly manufacturing technology are more likely to contain both patent (error) and latent defects because of the proximity of devices and interconnections contained within a small volume. The effects of poor heat dissipation in densely packaged electronic assemblies can accelerate latent defects to early failure. Difficulties in initially assembling or reworking the hardware can also make such assemblies more defect prone. Procedure B in Section 5, for estimating defect density, thus includes a packaging density factor. This factor should be continually monitored and refined using Procedure D of section 5.

4.4.4 Screen Selection and Placement. Planning a stress screening program requires the selection and placement of appropriate screens at various levels of assembly so as to achieve a cost effective screening program. Listed below are the factors which affect screen selection and placement. The factors are discussed in more detail in the following paragraphs.

a. Screening strength - The product of precipitation efficiency and detection efficiency, determines the capability for removing defects.

b. Precipitation efficiency - Prior knowledge of the effectiveness of the screens in precipitating defects to failure.

c. Detection efficiency - The tests which can be economically and feasibly used to detect defects which have been precipitated to failure by the screens

d. Thermal and vibration response characteristics - The structural, thermal and material properties of the items to be screened and their response to applied stress.

e. Design limits - The environmental stress design limits of the items to be screened.

f. Facilities - The screening, test and instrumentation facilities available to the manufacturer to perform screening and test operations.

g. Costs - The costs to achieve screening program goals on remaining defect density.

i. Product Reliability Verification Test (PRVT) - The use of a PRVT as an integral part of an ESS program to provide confidence that field reliability will be achieved.

4.4.4.1 **Precipitation Efficiency.** Precipitation efficiency is defined as the probability that a screen will precipitate a defect to a detectable state given that a defect susceptible to the screen stress is present. Screening strength is defined as the precipitation efficiency multiplied by the probability that the defect will be detected and removed (i.e., the detection efficiency). A basic premise of stress screening is that under specific screening stresses applied over time, the failure rates of defectives are accelerated from that which would occur under normal field operating stress conditions. By subjecting electronic items to accelerated stresses, i.e. rapid temperature cycling and random vibration, latent defects are thus precipitated to early failure. More severe stresses will tend to accelerate failure mechanisms and the rate of defect failure. For example, the failure rate of a latent defect increases with more rapid rates of temperature change and larger temperature extremes. The precipitation efficiency (and hence screening strength) of a random vibration screen increases as a function of the level and duration of the applied excitation.

Stress screens are not all equally effective in transforming latent defects into detectable failures. Table 4.3 provides a listing of latent defect types and the screens believed to be effective in precipitating them to failure. Table 4.3 may be used as an aid in the selection of a screen type when prior knowledge on workmanship or part defects for similar assemblies is not available.

Table 4.3: Assembly Defect Types Precipitated by Thermal & Vibration Screens

Defect Type	Thermal Screen	Vibration Screen
Defective Part	X	X
Broken Part	X	X
Improperly Installed Part	X	X
Solder Connection	X	X
PCB Etch, Shorts and Opens	X	X
Loose Contact		X
Wire Insulation	X	
Loose Wire Termination	X	X
Improper Crimp Or Mating	X	
Contamination	X	
Debris		X
Loose Hardware		X
Chafed, Pinched Wires		X
Parameter Drift	X	
Hermetic Seal Failure	X	
Adjacent Boards/Parts Shorting		X

Reference RADC-TR-82-87

Table 4.3 indicates that vibration screens are generally more effective for loose contacts, debris and loose hardware while temperature cycling screens are not effective. Thermal screens are generally more effective for part parameter drift, contamination and improper crimp or mating type defects while vibration screens are not. For other defect classes listed in the table, both thermal and vibration screens are effective, but the relative degree of effectiveness of one screen type over the other is not precisely known. These are some of the uncertainties which must be dealt with in planning a screening program. Historically, on average, 20% of the defects are found to be responsive to vibration screens and 80% to temperature cycling screens. (Reference publication IES Environmental Stress Screening Guidelines for Assemblies).

To improve the modeling accuracy and to ensure a proper balance between thermal and vibration screens, it is recommended that the defect population be segregated into Random Vibration (RV) sensitive defects and Temperature Cycle (TC) sensitive defects. If necessary, the population responsive to either TC or RV can also be included on the model.

4.4.4.1.1 Screen Parameters. Precipitation efficiency is a function of specific screen stresses (parameters) and the time duration of the stress application. Equations provided in Procedure C of Section 5 provide values for precipitation efficiency as a function of relevant screening parameters. It should be noted that these parameters pertain to the unit under test and not the chamber etc. Vibrational characteristics of the equipment (e.g., resonances, transmissibility etc.) and the various thermal conductivities and masses must be considered. All assembled hardware consists of many paths along which a stress might be transmitted. The selection of screening parameters and methods of stress application must be suited to the stress transmission characteristics of the hardware design. As a part of the screen selection and placement process, in which thermal or vibration screens are to be used, a stress response survey of the item to be screened should be performed. This may require simulations and or surveys conducted on the actual or similar hardware. Care should be exercised to ensure that hardware responses are large enough to generate an effective screen while not exceeding hardware design capability. Environmental stresses should be applied to the hardware and the response of critical hardware elements measured to determine whether maximum or minimum temperature limits are being exceeded, and whether suspected defect sites (parts, interconnections etc.) are responsive to the screen stress. In addition, normal design provisions for isolating the hardware from stress such as the use of shock mounting, vibration isolators or cooling air should also be evaluated. Application of environmental stress screening in such instances, should require bypassing the normal stress isolation provisions or may dictate the need for screening at lower assembly levels which do not include the stress isolation design features. Temperature cycle, constant temperature, random and swept-sine screening parameters are defined as follows:

a. Thermal cycle screen parameters

(1) Maximum temperature (T_{max}) - The maximum temperature to which the screened item will be exposed. This should not exceed the lowest of the maximum ratings of all the parts and materials comprising the item. Note that non-operating temperature ratings for parts are higher than operating ratings.

(2) Minimum temperature (T_{min}) - The minimum temperature to which the screened item will be exposed. This should not exceed the highest of the minimum ratings of all the parts and materials comprising the assembly.

Note: T_{max} and T_{min} must be carefully selected either through analytical means or a thermal survey.

(3) Range (R) - The range is the difference between the maximum and minimum applied external (chamber) temperature (T_{max} - T_{min}). Temperatures are expressed in ^{o}C. Care should be taken when Tmin is negative not to subtract incorrectly and result in an erroneously small computed temperature range.

(4) Temperature rate of change (T_R) - This parameter is the average rate of change of the temperature of the item to be screened as it transitions between T_{max} and T_{min} and is given by:

$$T_R = \frac{\left[\left(\frac{T_{max} - T_{min}}{t_1}\right) + \left(\frac{T_{max} - T_{min}}{t_2}\right)\right]}{2}$$

Where:

t_1 is the transition time from T_{min} to T_{max} in minutes

t_2 is the transition time from T_{max} to T_{min} in minutes

(5) Dwell - Maintaining the hardware temperature constant, once it has reached the maximum (or minimum) temperature, is referred to as dwell. The duration of the dwell is a function of differences in the thermal mass of the items being screened.

(6) Number of cycles - The number of transitions between temperature extremes (T_{max} or

T_{min}) divided by two.

b. Constant Temperature Screen Parameters

(1) Temperature delta (ΔT) - The absolute value of the difference between the hardware temperature and 25°C.

$$\Delta T = |T - 25\ ^{o}C|$$

Where T is the hardware temperature

(2) Duration - The time period over which the temperature is applied to the item being screened, in hours, after the hardware has reached thermal equilibrium.

c. Vibration Screen Parameters

(1) Grms level for random vibration - The rms value of the applied power spectral density observed by the hardware, including resonance and transmissibility effects.

(2) Spectrum shape for random vibration - The shape taken by the range of frequencies in the frequency spectrum.

(3) G-level for swept sine vibration - The constant rms acceleration applied to the equipment being screened throughout the frequency range above 40 HZ. The g-level below 40 HZ may be less.

(4) Sweep rate for swept sine vibration - The rate at which the "forcing" frequency is varied through a range of frequencies.

(5) Duration - The time period over which the vibration excitation is applied to the item being screened, in minutes.

(6) Axes of vibration - This can be a single axes or multiple axes depending on the sensitivity of defects to particular axial inputs.

4.4.4.1.2 Design Limits. The use of screen parameters which impose stresses which exceed the design limits of the product is not recommended. Effective screening programs can be developed without having to resort to stresses which exceed the design capability of the hardware. Criteria for judging how much the design limits can be safely exceeded, without causing damage to the product, are non-existent or at least arbitrary. However, to permit reasonably high ESS stress levels, it is important that the equipment be designed for ESS and thus the ESS program and required stress levels should be determined concurrently during the design stage. Designing equipment for ESS means that the design should develop such that individual assemblies have similar response characteristics. This should be done so that no one subassembly will be dictating the screening levels for the other subassemblies. Using the procedures contained in the handbook, the manufacturer can focus on those items in which defects are most likely to reside in the hardware and determine safe screening levels, within appropriate cost constraints, for precipitating them to failure. The procedures take into account the increased defects with increased factory stress level and also require a fatigue life study to ensure that useful operating life has not been impacted by the amount or level of ESS.

4.4.4.1.3 Guidelines for Initial Screen Selection and Placement. The development phase ESS program is intended to expose various defect types and causes and to obtain factory data to calculate and refine the planning estimates of D_{IN} and SS that were based on handbook and industry data. Additional ESS beyond that intended for production may be required to improve the estimate accuracy. An initial screening regimen should be selected for experimental use during the development phase in conjunction with the use of the handbook procedures. Table 4.4 is recommended as an aid in selecting and placing screens for a starting regimen.

4.4.4.1.4 **R&M 2000 ESS Initial Regimen**. R&M 2000 ESS studies recommend the screen types, parameters and placements outlined in Table 4.5 as an initial regimen. The screens contained in Table 4.5 have high precipitation efficiency. After sufficient fallout has been observed, the screening regimen may be reduced. The R&M 2000 guidelines thus represent initial values for consideration during the development phase and can be reduced for production based on the planning and analysis procedures outlined in Procedures A and D.

4.4.4.2 **Detection Efficiency**. Detection efficiency is a measure of the ability to detect and remove patent defects. Detection efficiency includes factors representing fault coverage, the requirement for concurrent stress, he test duration, and the diagnostics and rework capabilities for removing the defect. Detection efficiency is expressed as the ratio of patent defects detected (and removed) by a defined test procedure to the total possible number of patent defects. While stress screens may be effective in precipitating a latent defect into a detectable failure, removal of the failed condition is dependent on the capability of the test procedures used to detect and localize the failure.

Care should be taken to ensure that tests have detection efficiencies as high as is technically and economically achievable. The screens may otherwise precipitate defects to failure which may go undetected by post screen tests. Modern electronic equipment comprised of microprocessors, large memory and LSI devices may contain defects so subtle that only the most thorough of tests can detect them. High screening strengths at lower levels of assembly may not always be easily accomplished because of low detection efficiency. The difficulty in accurately simulating functional interfaces or the inability to establish meaningful acceptance criteria may make the development of tests with high detection efficiency at the assembly level difficult and costly. A certain percentage of defects may only be detectable at the unit/system level when all or a majority of the system components are connected and operating as a system. Analysis and quantification of detection efficiencies should be an integral part of the planning for a screening program.

4.4.4.2.1 **Determining Detection Efficiency**. Detection efficiency is determined as the product of factors that represent the following considerations:

(a) The probability of observing and detecting a patent defect. This includes the probability of detection and the probability of occurrence. Consideration must also be given to the extent that the tests and limits being used represent all application requirements for functional and parametric performance. The detection of intermittent and/or situation sensitive defects may also require extended test times and may be modeled using a Poisson distribution.

(b) The requirement for concurrent stress. Many of the latent flaws precipitated to failure by ESS can only be detected when stress is applied during the test.

(c) The probability of isolating and then removing the defect without creating an additional defect.

On some system procurements the probability of detection is a specified parameter for built-in-test (BIT), performance monitoring (PM) and fault location (FL) capability requirements. When the required BIT or PM/FL capability is used to verify performance of an item being screened, the actual values of fault coverage should be used in conjunction with the factors defined above and in Procedure C. On other system procurements, requirements to perform a failure modes and effects analysis (FMEA) are specified in the contract. In such cases, the FMEA should be used to estimate the fault coverage for a given test design.

When FMEA or BIT fault detection requirements are not specified in the contract, estimates of fault coverage should be made based upon experience data. Appendix C provides values of fault coverage for various tests which may be applied with stress screens. The values in the table were derived by production and engineering test personnel from a large DOD electronic system manufacturer. RADC TR-82-87

Table 4.4: Guidelines for Initial Screen Selection And Placement

<table>
<tr><th rowspan="2">LEVEL OF ASSEMBLY</th><th colspan="4">SELECTION</th><th colspan="2">PLACEMENT</th></tr>
<tr><th>TEMP. CYCLE</th><th>CONST. TEMP</th><th>RAND. VIB.</th><th>S.S. VIB</th><th>ADVANTAGES</th><th>DISADVANTAGES</th></tr>
<tr><td rowspan="2">ASSEMBLY</td><td>E^1</td><td>M^2</td><td>M^3</td><td>N</td><td rowspan="2">• Cost per flaw precipitated is lowest (unpowered screens).
• Small size permits batch screening.
• Low thermal mass allows high rates of temperature change.
• Temperature range greater than operating range allowable.</td><td rowspan="2">• Test detection efficiency is relatively low.
• Test equipment cost for powered screens is high.</td></tr>
<tr><td colspan="4">E - Effective
M - Marginally Effective
N - Not Effective

Notes:
1. Particularly if power is applied and performance is monitored at temperature extremes.
2. Effective where assemblies contain complex devices (RAMS, microprocessors, hybrids, etc.)
3. Effectiveness highly dependent on assembly structure. Not effective for small, stiff PWAs.</td></tr>
<tr><td rowspan="2">UNIT</td><td>E</td><td>M</td><td>E</td><td>M</td><td rowspan="2">• Relatively easy to power and monitor performance during screen.
• Higher test detection efficiency than assembly level.
• Assembly interconnections (e.g. wiring backplane) are screened.</td><td rowspan="2">• Thermal mass precludes high rates of change, or requires costly facilities.
• Cost per flaw significantly higher than assembly level.
• Temperature range reduced from assembly level.</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="2">SYSTEM</td><td>E</td><td>M</td><td>E</td><td>M</td><td rowspan="2">• All potential sources of flaws are screened.
• Unit interoperability flaws detected.
• High test detection efficiency.</td><td rowspan="2">• Difficult and costly to test at temperature extremes.
• Mass precludes use of effective vibration screens, or makes use costly.
• Cost per flaw is highest.</td></tr>
<tr><td colspan="4"></td></tr>
</table>

Table 4.5: R & M 2000 Environmental Stress Screening Initial Regimen

SCREEN TYPE PARAMETERS AND CONDITIONS	ASSEMBLIES (PRINTED WIRING ASSEMBLIES) (SRU)	EQUIPMENT, OR UNIT (LRU/LRM)
THERMAL CYCLING SCREEN		
Temperature Range (Minimum) (See Note 1)	From -54°C To $+85^{\circ}$C	From -54°C To $+71^{\circ}$C
Temperature Rate Of Change (Minimum) (See Note 2)	30°C/Minute (Chamber Air Temp.)	5°C/Minute (Chamber Air Temp.)
Temperature Dwell Duration (See Note 3)	Until Stabilization	Until Stabilization
Temperature Cycles (Minimum)	25	10
Power On/Equipment Operating	No	(See Note 5)
Equipment Monitoring	No	(See Note 6)
Electrical Testing After Screen	Yes(At Ambient Temp)	Yes(At Ambient Temp)
QUAS-RANDOM VIBRATION (See Note 7)		
Spectral Density	(See Note 8)	6 Grms
Frequency Limits		100 -1000 HZ
Axes Stimulated Serially or Concurrently		3
Duration Of Vibration (Minimum)		
- Axes Stimulated Serially		10 Minutes/Axis
- Axes Stimulated Concurrently		10 Minutes
Power On/Equipment Operation		(See Note 5)
Equipment Monitoring		(See Note 6)

* SRU - Shop Replaceable Unit LRU - Line Replaceable Unit LRM - Line Replaceable Module

Notes:

1. Temperatures beyond stated minimums are acceptable.
2. Rapid transfers of the equipment between one chamber at maximum temperature and another chamber at minimum temperature are acceptable.
3. The temperature has stabilized when the temperature of the part of the test item considered to have the longest thermal lag is changing no more than 2 degrees Centigrade per hour.
4. A minimum of five thermal cycles must be completed after the random vibration screen.
5. Shall occur during the low to high temperature excursion of the chamber and during vibration. If operating, equipment shall be at maximum power loading. Power will be OFF on the high to low temperature excursion until stabilized at the low temperature. Power will be turned ON and OFF a minimum of three times at temperature extremes on each cycle.
6. Instantaneous go/no-go performance monitoring during the stress screen is essential to identify intermittent failures when power is on.
7. Specific level may be tailored to individual hardware specimen based on vibration response survey and operational requirements.
8. When random vibration is applied at the equipment- level, random vibration is not required at the subassembly-level. However, subassemblies purchased as spares are required to undergo the same random vibration required for the equipment-level. A "LRU mock-up" or equivalent approach is acceptable.

4.4.4.2.2 Power-On Testing vs Power-Off. Application of power, exercising and monitoring equipment performance continuously during the screen will greatly enhance detection efficiency. Subtle faults, such as contact intermittents or temperature sensitive parts, can only be detected with powered and monitored screens. With the increased complexity of modern electronics, fault sites may be confined to smaller areas and fault symptoms may appear only during certain tests or under a special set of external conditions. As a result, a greater incidence of "Cannot Duplicate"(CND), "No-Fault Found" (NFF) and "Retest OK"(RTOK) and similar intermittent or transient phenomena can occur. Patent defects which have been precipitated to failure by stress screens can be categorized into three general types:

a. Type 1. Physical defects transformed from an inherent weakness to a hard failure by the stress screen.
b. Type 2. Physical defects that manifest as failures only while under thermal or mechanical stress. (e.g. intermittent caused by a cold solder joint).
c. Type 3. Functional defects that manifest as performance failures or anomalies only while under thermal or mechanical stress. (e.g. timing problems).

The type 1 defects are readily detected by post screen tests of sufficient thoroughness. Type 2 and Type 3 defects require thorough and continuously monitored tests so that they can be detected. Type 3 defects, which include problems such as timing, part parameter drift with temperature or tolerance build-up can only be detected with powered and monitored tests. Type 2 and Type 3 defects can comprise 50% and as much as 80% of the latent defects present in the hardware. (Reference RADC TR-86-149)

Developing tests and test strategies for use with stress screens and estimating their detection efficiency is a vitally important activity in planning a stress screening program. The use of tests with high detection efficiency is of equal importance to using screens with high precipitation efficiency in structuring a screening program for production.

4.4.4.2.3 Pre/Post Screen Testing and Screening Strength. In order to experimentally determine screening strength, the following conditions are required:

a. The items subjected to stress screening must be tested thoroughly before the stress screen to assure that no detectable failures remain at the start of stress screening. When testing is not performed prior to stress screening, it is not known whether patent defects were present, which could have been detected without stress screening, or whether latent defects were precipitated by the stress screen.

b. The items subjected to stress screening must be powered and exercised. Performance must be continuously monitored to assure that stress-dependent defects (e.g., intermittents, temperature and timing sensitive faults) are detected.

c. The items subjected to screening must be tested using the same test(s) both before and after the stress screen to assure that the failures detected are a result of the stresses imposed.

d. Data must be collected on defect fallout after the stress screen (i.e. , during subsequent stress screens, tests, or early field operation) to obtain an estimate of the number of defects which were initially present.

When such data are available and assuming perfect tests, then the screening strength can be determined by use of the observed fallout from the screen and the number of defects initially present i.e.:

$$\text{Screening Strength} = \frac{\text{Fallout}}{\text{Number Of Initial Latent Defects}}$$

However, the total number of latent defects can not be determined until extensive field data is available. We are thus compelled to use a modeling approach where screening strength is based upon estimates derived from a combination of the actual screening program data, experiments, and the published literature. The precipitation efficiency models and values used in the handbook tables of Procedure C in Section 5, were developed using such an approach. The results and methodology used for these studies are contained in RADC TR-82-87 and RADC TR-86-149. Additional information is also provided in AFWAL TR-80-3086 and ADR 14-04-73. As more experience data on stress screening are gathered, the screening strength estimates will be refined and improved.

4.4.4.2.4 **Production Phase - Refining Estimates From Fallout Observation**. The analysis methodology provided in Procedure D is based upon curve fitting actual data to determine the latent and patent defect components. Defects present before screening appear as the D_{PAT} term and defects precipitated and detected by the screen appear as the D_{LAT} term. This approach, however, requires a sufficient number of data points throughout the screen. If changes take place during production such as in an assembly or fabrication process, personnel or production flow, then the defect density (both latent and patent) is likely to change and affect the fallout observed during screening and will be apparent using the monitoring and control procedures of Procedure E. Under long term production, process improvements and other corrective actions taken as a result of the screening process are likely to change the quantity and distribution of latent defects present in the hardware.

4.5 **Production Phase - Monitoring Evaluation and Control.** Once a screening program is implemented during the production phase, the screen fallout data and the screening process must be monitored and controlled to assure that program objectives are achieved. For an effective monitoring and control program, the field reliability requirements should be directly related to goals and requirements for parts, processes, and materials and assemblies for all factory integration and ESS test levels. The procedure for establishing these requirements and for monitor and control are provided in Procedures A and E respectively. Use of a Failure Reporting Analysis, and Corrective Action System (FRACAS) should be an integral part of production phase monitoring and control tasks. The fallout from the screening process provides the necessary visibility regarding the sources of defects in the product and the manufacturing process. Finding defects, determining their root causes and ensuring that the sources of the defects are eliminated from either the process or product, is the basic mechanism by which process capability is improved.

Analyses of screen fallout data must be performed with specific objectives in mind. Well-defined monitoring, evaluation and control task objectives will ensure that the proper data is collected, classified and correctly analyzed to meet objectives. The objectives of the monitoring-evaluation and control tasks are to establish assurance that remaining defect density and reliability goals are achieved through implementing improvements in manufacturing, screening and test process capability. Manufacturing process capability is improved through taking corrective actions which reduce the number of defects that are introduced into the product. Screening process capability is improved by increasing both the precipitation efficiency of screens (by ensuring that potential sites for defects in the product are being adequately stimulated) and the detection efficiency.

Another goal of monitoring and control is related to cost effectiveness. The initial screening program might have been based upon planning estimates which were overly pessimistic. Corrective actions might also have been taken during production to reduce the number of defects introduced into the product. In either case, if the screening program is continued as planned, more screening than is necessary results, which impacts both cost and schedule. Decisions must be made on how to reduce the screening regimen. In a sense, the goal of ESS and the monitoring and control tasks is to make the screening program unnecessary (except for that limiting value required for PRVT).

4.5.1 **Data Collection.** The importance of timely and accurate data collection to achieving screening program objectives cannot be overemphasized. The data elements listed below should be collected during the conduct of the screening program. Some of the data elements become available directly as observed events from the screening process. Other data elements will become available only after analysis of the failures and failure data, or after a batch of items have been exposed to screening.

a. Identification of the items exposed to the screen/test, e.g., description, part number, revision, and serial number.

b. Number of like items exposed to the screen/test.

c. Number of like items passed/failed the screen/test.

d. Date of test

e. Test station or equivalent

f. Type and number of defects found in conjunction with the number of items exposed, passed/failed (data elements b, c, d).

g. Description of the type of defect found (part, workmanship/process, design)

h. Identification of the part, interconnection site where the defect was found.

i. Identification of the assembly level or manufacturing process operation where the defect was introduced.

j. Screen conditions under which the defect was found (e.g., high temperature, vertical axis of vibration etc.).

k. Time-to-failure relative to the start of the screen.

l. Failure analysis results which identify the root cause of the defect.

m. Corrective action taken to eliminate the cause of the defect from the product and/or process.

Data elements l and m may only be available if trends, as identified by the SPC monitoring and control methodology, warrant detailed root cause analysis and corrective action.

4.5.2 Failure Classification. In order to establish a basis for the analysis of the screening fallout data, the failures must be properly classified. The following classification scheme is recommended.

a. Part defect - A failure or malfunction which is attributable to a basic weakness or flaw in a part (diode, transistor, microcircuit, etc.) Subcategories may include electrical, electronic, and mechanical.

b. Manufacturing defect - A failure or malfunction attributable to workmanship or to the manufacturing process (cold solder joint, cracked etch, broken wire strands, etc.) Subcategories may include assembly, process, and handling.

c. Design Failure - A failure or malfunction attributable to a design deficiency. Note that electrical or thermal overstress failures due to inadequate derating, are design problems. Subcategories include hardware and software.

d. Externally induced failures - A failure attributable to external influences such as prime power disturbances, test equipment, instrumentation malfunctions or test personnel.

e. Dependent failure - A failure which is caused by the failure of another associated item which failed independently.

f. Unknown cause failure - An independent failure which requires repair and rework but which cannot be classified into any of the above categories. An intermittent failure that recurs infrequently would be an unknown cause. Subcategories include verified and not verified.

g. Unable to verify (UTV), retest OK (RTOK), and NO Fault Found (NFF) classifications describe conditions where an anomaly during testing could not be reproduced.

4.5.3 Preliminary Analysis of Fallout Data. A preliminary analysis of the fallout data should be performed to ensure that failure causes are properly established and to categorize the failures so that more detailed analysis related to the ESS program objectives can be performed.

a. All failures traceable to part, board and interconnection defects, which are precipitated and detected by a screen/test, should be considered to be latent defects provided that pre-screen testing was performed. These data should be used for monitor and control purposes.

b. A predominance of design problems which are discovered during production screening operations is a matter of serious concern. Every effort should be made to determine corrective actions for design problems very early in production. It does no good to speculate that the design problems should have been eliminated from the hardware during the development stage. Stress screening, on a 100% basis, is an expensive and time consuming method for finding design problems. If the fallout from screening indicates persistent evidence of design problems, methods other than 100% stress screening should be used. Reliability growth and Test-Analyze-And-Fix (TAAF) techniques are recommended.

c. Special attention should be given to unknown cause failures. Sufficient investigation should be made to establish that an intermittent condition does not exist. The number of failures classified as "Unknown Cause" should be kept to a minimum. Every effort should be made to correlate the failure circumstance data with the other similar failure incidents, as well as to use failure analysis so as to establish the cause of failure. The number of "unknown cause" classifications and/or "unable to verify" classifications should be used in assessing the detection efficiency.

d. Analyses of induced failures should be performed to determine necessary corrective actions.

The detailed analyses would typically be performed if the established goals and requirements are not being achieved, either for parts, materials and processes or for assemblies at various ESS levels.

4.5.4 Analysis of Screen Fallout Data. The analysis of screening fallout data is directed toward evaluating the screening process so as to achieve screening program goals on remaining defect density, $D_{REMAINING}$. Yield goals are achieved by both improving manufacturing process capability through corrective action and by improving the screening and test process capability when it is found to be needed.

Manufacturing, screening and test process capability will determine the remaining defect density. The capability of these processes are measured and controlled by use of two important quantities, the incoming defect density (D_{IN}) and the screening strength (SS). Neither one of these quantities are directly observable as a result of the screening process. The only observable statistic is the fallout from the screen/test, from which inferences regarding D_{IN} and SS must be drawn. The basic approach used in Procedure D of Section 5, is to obtain estimates of D_{IN} and SS, using the screen fallout data and to statistically compare the observed data against the planning estimates. Based upon the comparisons, corrective actions are determined to eliminate the source of the defect from the process and/or to change the screens so as to achieve stated objectives.

Two complementary procedures are presented in Procedures D and E for performing monitoring and analyses tasks. Procedure D uses curve fitting techniques, applied to the mathematical model, to estimate D_{IN} and SS. Procedure E uses Quality Control Charts (SPC and PARETO) for monitoring and control.

Quality control charts. The use of control charts for defect control is a standard technique. Control charts (SPC and PARETO) are used in Procedure E which are based upon the Poisson Probability distribution; i.e.,

$$P(x) = \frac{\exp(-D)D^x}{x!}$$

Where:
D = defect density
x = number of defects in an item
P(x) = probability of x defects in an item

The mean of the Poisson distribution is D and the standard deviation is $\sqrt{D}$. The primary purpose of the control chart technique is to establish baselines against which the process can be monitored and by which out-of-control conditions can be identified. Because of varying conditions, for example improving defect density, the actual defect density, D is determined using regression analysis. This value is then used to determine the expected statistical variation due to limited sample size i.e. $D \pm n\frac{\sqrt{D}}{N}$ where n is the number of standard deviations, typically 3, and N is the sample or lot size. Defect density is calculated, using the fallout data, and compared against the control chart baselines. Part and workmanship (process) problems are rank ordered with consideration for the expected defects based on complexity, etc., and analyses are performed and corrective actions taken to eliminate the source of the defects from the product. Procedure E of Section 5 contains the detailed methodology for implementing the control chart technique.

4.5.4.1 Use of the Mathematical Model to Evaluate Screening Results. Appendix A provides a description of the Stress Screening Mathematical Model. The factory fallout data (expressed defects per system) can be curve fitted to the expression developed therein (for $D_{REMOVED}$) so as to obtain estimates of the model parameters. Parameters which can be determined using this method are D_{IN}, SS (comprising PE and DE terms), the constant failure rate (CFR) and SAF, a stress adjustment factor relating defect levels at field stress to factory stress.

4.5.4.2 Use of the Chance Defective Exponential (CDE) Model to Evaluate Screening Results. The defect distribution for both factory and field stress environments have been empirically determined to be represented by the following expression.

$$D_{REMOVED} = DE^{*}[\, D_{PAT} + D_{LAT}^{*}(1\text{-}\exp(\text{-}kt)) + CFR^{*}t \,]$$

where D_{PAT} represents the patent defects, D_{LAT} represents the latent defects, t the stress duration e.g. time, cycles etc., k the precipitation stress constant, CFR the constant failure rate, and DE is the detection efficiency which is 1 for the field.

The CDE model developed by Fertig and Muthy and discussed in a paper contained in the 1978 Annual R&M Symposium provides a possible explanation for this observed relationship.

Regardless of the true derivation, the empirical results have been found to be sufficiently accurate for the purposes of this handbook. Inaccuracies either in the modelling and/or the estimated parameters are initially addressed using design margins and addressed during the production phase through the use of actual factory and field data to refine the estimates. The observed fallout data can be fitted to the model to obtain estimates of the model parameters. The parameters of the model provide estimates of the incoming defect density D_{IN}, the screening strength (SS, PE, DE), the limiting failure rate of the equipment (CFR) and the stress adjustment factor (SAF). Figure 4.3 is an extract from a study report which shows a histogram of the screen fallout from a 12 cycle -54°C to 71°C temperature cycle screen. The fallout per cycle is used to obtain maximum likelihood estimate (MLE) for the parameters of the CDE model.

As Figure 4.3 shows, the CDE model parameters estimated by the MLE procedure are: incoming defect density (D_{IN}) equal to .1542 defects per item, the failure rate of a defect (Dk) equal to .1485 failures per hour (which corresponds to a screening strength of .95 and a value of .0032 for the limiting failure rate (CFR).

4.5.4.3 Product Reliability Verification Test (PRVT). The use of a PRVT segment as part of an ESS program is intended to provide confidence that field reliability will be achieved and help identify out of control conditions that could otherwise be missed. As defect density is improved, ESS can be reduced to optimize cost without impacting field reliability. However, ESS can not be completely eliminated since some portion is required to allow reliability to be assessed. PRVT is that portion of ESS retained for this purpose.

Assessments of reliability should be made on the basis of the performance of the collective population. The PRVT segment should be implemented on a first pass yield basis (first pass yield being defined as the number of systems completing the PRVT segment with no failures divided by the total number of systems submitted first time). If the first pass yield requirements are not achieved, corrective actions must be taken that address the entire population. Appendix B provides the mathematical derivation of the PRVT methods contained in the handbook. Procedure F in Section 5 contains the detailed procedures for incorporating the PRVT segment.

Note that a failure free requirement for any part of ESS or PRVT is not recommended. If requirements (e.g., PRVT yield) are not being achieved and defects are randomly distributed, then the overall defect density is too high and action must be taken that affects the entire population. Requiring one particular piece of equipment to pass a sequence of tests "failure free" does not substantially improve the reliability of the population. The failed item however, must undergo sufficient confidence testing subsequent to rework to ensure that the fault has been eliminated.

4.6 Costs of ESS vs Productivity Improvement. The costs of conducting a screening program during the production phase can be high. To a large extent, the costs can be offset by the increased productivity which results through proper screen selection and placement. Screening at the lowest possible level of assembly will almost always be the least costly alternative in terms of rework costs. The time and effort required to test, troubleshoot and repair items increases by at least an order of magnitude at each subsequent level of assembly. Significant cost savings or avoidance can accrue to the manufacturer by analyzing the cost benefits of various screen selection and placement alternatives and by striving to find defects at the lowest possible level of assembly. The fixed and recurring costs to screen, instrument, and test the hardware at lower assembly levels (especially with power applied) can possibly negate any benefit from lower rework costs. It is imperative that the optimum ESS program be determined for each equipment type. Cost savings to the Government will result through improved field reliability and corresponding reductions in field repair costs. The benefits of a properly conducted ESS program to the Government go beyond field repair costs alone. Improved reliability during early life will also reduce over-buying of spares, since estimates of required spare quantities are based upon early life field performance. The opportunity for introducing new defect sources into the hardware during field maintenance and handling is also reduced.

There should be however, controls and constraints on the cost of conducting a screening program. Situations can arise where the cost of conducting a screening program far outweigh any benefits which may be derived. For example, for low complexity items the number of screenable defects which are likely to be present in the hardware may be relatively small. Conducting a full-scale screening program, in such cases, can result in very high costs per defect eliminated. Costs of $10K to $15K per defect eliminated may be justified for equipments which are used in critical missions with very high reliability requirements. On the other hand, such costs may be difficult to justify if the equipment is used in non critical missions and if the costs of field maintenance are not severely effected by not screening. Each case, where a stress screening program is under consideration, must be judged individually as to the cost benefits to be derived from stress screening and optimized on a combined user-producer cost basis. Procedure A, in Section 5 is used to determine the cost effectiveness of ESS programs.

4.6.1 Facilities and Costs. The facilities that the manufacturer has available for screening, instrumenting and testing the product affects screen selection and placement. A manufacturer may not have random vibration facilities or automatic test systems which can be used for the stress screening program. In such cases, the manufacturer may decide to impose less severe stresses for a longer duration or decide to use less expensive alternatives such as described in NAVMAT P-9492. The costs to purchase expensive screening or test equipment and perform screens at a given level of assembly may not be warranted, in terms of the number of defects which are likely to be found. The screening and test facilities which the manufacturer has available for screening must be addressed in preparing the screening program plan and in the screen selection and placement process. Costs versus the benefits to be derived from screening should be addressed.

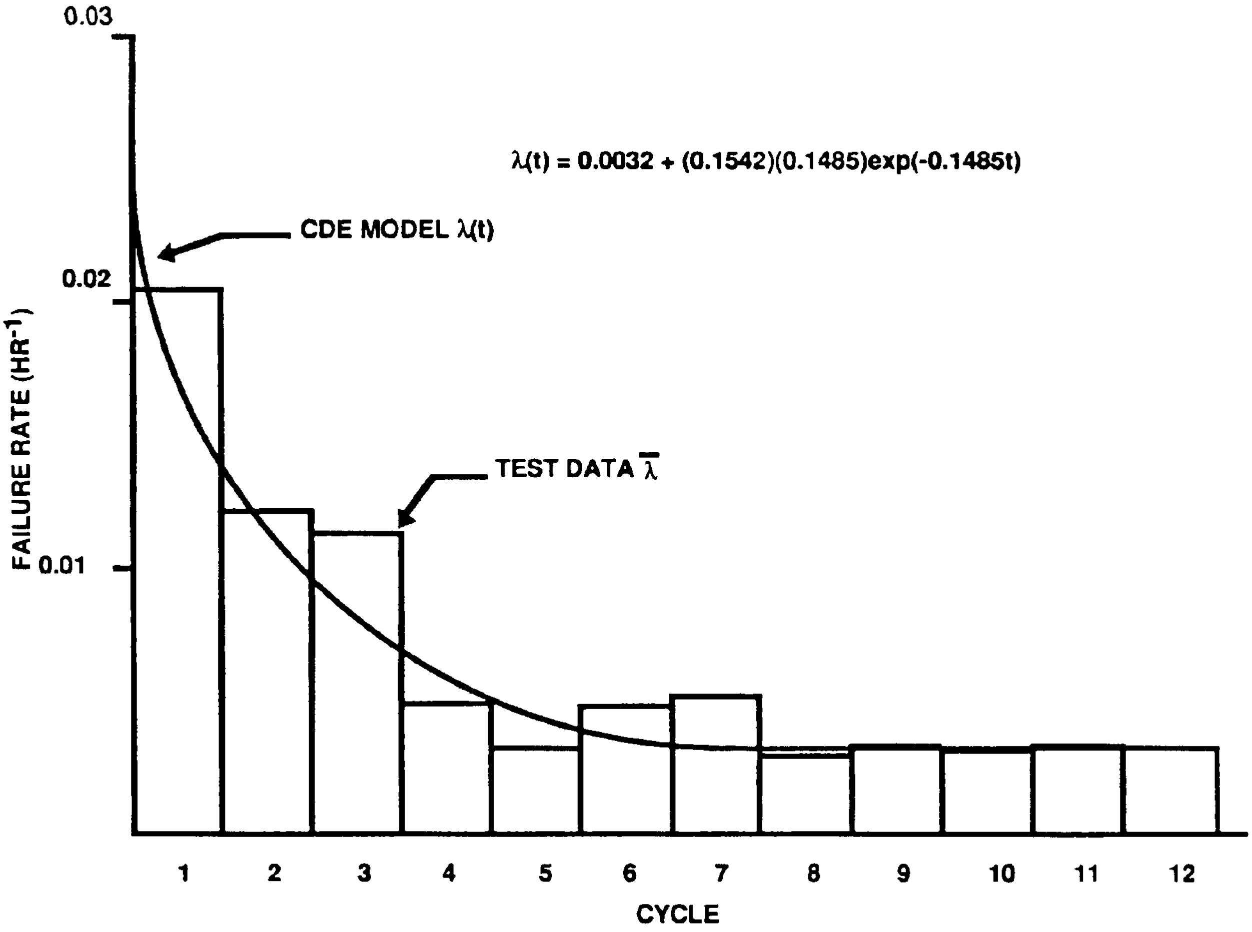


Figure 4.3: Temperature Cycling Data Fitted to the Chance Defective Exponential Model Reference AFWAL-TR-80-3086

The criterion used in the handbook to judge cost effectiveness is the combined cost to the producer and customer. If the cost per defect eliminated is found to be higher than required or optimum, then the manufacturer should determine alternative methods which lower the costs of finding and eliminating the defects. Alternatives might include reducing the incoming defect density by means other than assembly screening, (e.g., increase the quality level of parts used) increase the screening strength at lower assembly levels, or eliminate screens which may be of questionable value. In those cases, where field reliability is an overriding requirement, then the Government procuring activity must decide on the appropriate cost-reliability trade-off.

The procedures contained in the handbook not only optimize the screen selection and placement but also provide management with tools and methodology to optimize resource allocations and to assess the cost trade-offs between defect prevention through analysis and corrective action, and screening.

5. DETAILED GUIDELINES

5.1 ESS Implementation Procedures. The following paragraphs outline the procedures required to design, implement, and monitor a factory ESS program with the objective of continuously reducing defects through preventive actions such that ESS can be reduced to a minimum (and ideally eliminated except for that portion required for PRVT). The procedures are aimed at optimizing the combined user/producer cost of achieving a required field reliability under prevailing conditions.

An ESS program consists of three phases - planning, development, and production.

The planning phase is used to (a) design a cost optimized factory ESS program that achieves the required field reliability for an existing design and defect density, and to (b) create a suite of quantitative factory requirements that are meaningfully related to the required reliability and are measurable and monitorable by the producer. The planning phase uses defect density and screening strength data provided in the handbook and industry and user's data. Since the data are approximations, the values must be validated and refined during the development phase.

During the development phase, monitor and control procedures are used to quantitatively measure fallout data and thus refine the estimates for defect density and screening strength so that appropriate modifications can be made for production. Similar procedures are used throughout the production phase to provide a quantitative assessment and feedback on whether or not reliability requirements are being achieved and the extent that continuous improvement is being realized. If problems exist, the procedures assist in focusing on problem areas and/or identifying the areas requiring more in depth or root cause analysis. The methodology allows for a continual reduction in ESS/screening as defect densities are reduced through corrective action (provided customer reliability requirements are satisfied) and thus allows the user and producer to optimize the product cost and reliability. The procedures also provide management with the necessary visibility and models for assessing the tradeoffs between defect prevention and screening and assessing the return and effectiveness of resource allocations.

The ESS program includes a PRVT segment that is used in conjunction with ESS data analysis to provided the necessary confidence that field reliability will be achieved. The PRVT segment is calibrated during the development phase and is a fixed segment of the system level factory ESS. As defects are prevented through corrective action and ESS consequently reduced, the PRVT segment becomes useful in flagging possible out of control conditions that could otherwise be missed (due to the reduced ESS). The PRVT segment thus serves multi-purpose roles for ESS polishing, field reliability indication, and out of control identification.

There are a total of six procedures:

a. Procedure A entitled, "Optimizing Screen Selection and Placement" uses procedures B and C (which estimate defect density and screening strength respectively) to design the ESS program, and Procedure D to validate the original estimates of defect density and screening strength and refine the program. This procedure also optimizes the cost of an ESS program.

b. Procedure B entitled, "Estimating Defect Density" is used to estimate the incoming defect density.

c. Procedure C entitled, "Estimating Screening Strength" is used to estimate the screening strength.

d. Procedure D entitled, "Refining Estimates of Defect Density and Screening Strength" is used to analyze factory fallout data to provide revised estimates of D_{IN} and SS.

e. Procedure E entitled, "Monitor and Control" is used to provide a quantitative assessment of whether reliability requirements are being attained and to what extent continuous improvement is being realized.

f. Procedure F entitled, "Product Reliability Verification Test (PRVT)" is used in conjunction with Procedure E for monitor and control purposes to provide confidence that field reliability will be achieved.

5.2 Procedure A - Optimizing Screen Selection and Placement.

5.2.1 **Objective.** To plan an ESS program such that the required field reliability is attained at an optimum combined user-producer cost.

5.2.2 **Methodology.** The field reliability is determined by the latent defects remaining at the time of shipment and the existence of non-screenable defects that result in a constant failure rate. The objective of this procedure is to optimize the cost of reducing the latent defect population to an acceptable level defined as that which achieves the required field reliability. In planning an ESS program the first step is to determine the maximum allowable remaining latent defects that allow the required reliability to be achieved. Having determined the maximum allowable remaining defects, the required factory screening strength is determined from the estimated initial defects (D_{IN} - determined in Procedure B) by solving the equation:

$$SS = \frac{D_{REMOVED}}{D_{IN}} \qquad \text{where } D_{REMOVED} = D_{IN} - D_{REMAINING}$$

Knowing the required factory screening strength, the next step is to optimize the screen selection and placement based on the combined user-producer cost. This is accomplished by determining the cost of removing the required number of defects using various ESS options.

There are essentially three stages for applying this procedure. During the design stage initial estimates of D_{IN} and SS are derived using the mathematical modeling techniques of Appendix A and the data included in Procedures B and C augmented by any prior production history (collected and analyzed according to the techniques of Procedure D) from similar equipment. A design safety margin is built in to account for accuracy limitations of the estimates. During the development and/or early production phase, additional ESS may be added to provide sufficient data to use the curve fitting technique of Procedure D to "calibrate" the factors determined in the design stage. A minimum of 2 RV cycles and 10 TC cycles are recommended. During the production phase the curve fitting techniques of Procedure D are used to refine and validate the program on a continual basis.

5.2.3 Procedure Steps.

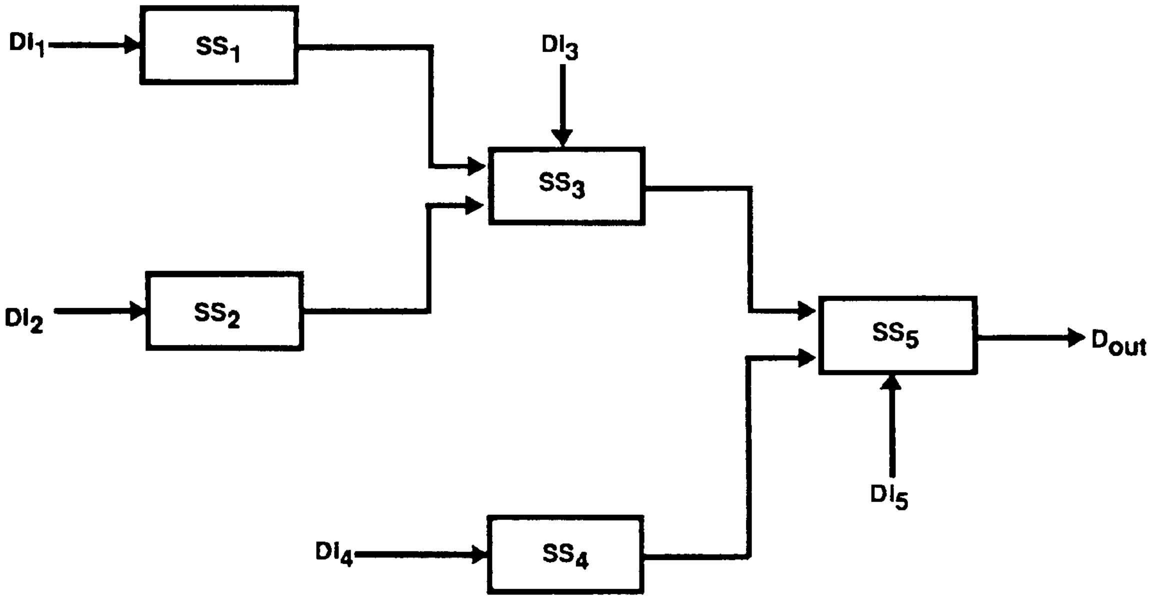
Procedure A1. The objective of this procedure is to create the basic ESS model for a particular program and to determine the incoming defect density, allowable outgoing defect density, and factory ESS constraints.

Step 1. Determine the initial defects resident in each assembly at all test and integration levels using the methods of Procedure B. Proportion the defects into RV and TC sensitive populations using the ratio 20% RV, 80% TC (ref. 4.4.4.1) or other suitably determined ratio.

Step 2. Determine the factory integration sequence and define all restrictions and requirements with respect to assembly, calibration, and acceptance testing. For example, determine exactly when in the factory integration sequence any sub-assembly calibration procedure should be performed. Allow for final ATP and test over environment. Prepare a multi-level ESS flow diagram depicting the integration and environmental testing requirements as illustrated in Figure 5.1. This diagram illustrates the production flow and provides the framework for ESS selection and placement.

Step 3. Use Procedure A2 to select and place RV and TC screens at various locations in the ESS model (flow diagram) created in step 2 above.

Step 4. Use Procedure C to determine the screening strength for various ESS options selected in Procedure A2. The model and calculations for a multilevel ESS flow are illustrated in Figure 5.1. Note: The method of computation shown is more accurate for the same kind of defects, i.e. RV and TC sensitive should not be mixed in this type of computation.



$$\begin{aligned} D_{OUT} = {} & DI_1(1 - SS_1)(1 - SS_3)(1 - SS_5) \\ & + DI_2(1 - SS_2)(1 - SS_3)(1 - SS_5) \\ & + DI_3(1 - SS_3)(1 - SS_5) \\ & + DI_4(1 - SS_4)(1 - SS_5) \\ & + DI_5(1 - SS_5) \end{aligned}$$

Figure 5.1: Sample Multi Level ESS Flow Diagram

Step 5. Given the customer's reliability requirements, determine the maximum number of defects permissible at the time of shipment that allow this reliability to be achieved. This is a three stage process as follows:

a) Determine whether the equipment has a limiting MTBF, i.e., the maximum inherent MTBF. The limiting inherent MTBF is the maximum that can be achieved and is limited by the state of the art in design, parts, materials, and processes and should be obtained from experience data from similar equipment.

b) Given the customer's required MTBF and using a suitable design safety margin to allow for estimation errors (typically 1.5 to 2) calculate the permissible failure rate (FR) due to latent defects using the expression:

$$\text{FR(due to latent)} \le \left(\frac{1}{\text{Required MTBF}} - \frac{1}{\text{Inherent MTBF}} \right) \text{X} \frac{1}{\text{SAFETY MARGIN}}$$

c) To determine the maximum number of defects permissible at the time of shipment it is necessary to determine the relationship between failure rate and remaining defects $D_{REMAINING}$. The derivation of the equation to be used to determine $D_{REMAINING}$ follows.

$$1.)\ FR = \frac{D_{FIELD}(t)}{t}$$

where t is the period over which MTBF is to be measured and D_{FIELD} is the number of field failures due to latent defects occurring during the interval t.

$$2.)\ D_{FIELD}(t) = D_{REMAINING} * SS_{FIELD}(t))$$

where $SS_{FIELD}(t)$ is the equivalent screening strength of the field environment for a period t.

$$3.)\ SS_{FIELD}(t) = 1\text{-}\exp(-kt)$$

where k is the field precipitation rate

Substituting (2) and (3) into (1) gives

$$FR = D_{REAMAINING}(\text{field stress})\frac{[1 - \exp(-kt)]}{t}$$

Solving for $D_{REMAINING}$ yields:

$$D_{REMAINING}(\text{field stress}) = \frac{FR*t}{1 - \exp(-kt)}$$

In this expression $D_{REMAINING}$ (the number of defects remaining after factory screening), t and k are all defined with respect to the field stress. It is thus necessary to modify this expression by the stress adjustment factor (SAF) determined in Procedure B to determine the remaining defects at factory stress.

$$\boxed{D_{REMAINING} = \frac{FR*t}{SAF[1 - \exp(-kt)]}}$$

This expression is applicable to both the RV and TC sensitive defect populations. Recall from step 1 of procedure A1 to proportion the defects into appropriate RV and TC sensitive populations.

There are two methods for determining the value of k.

(i) If the field application environmental stresses are known, calculate k using the expressions given in step 1 of Procedure C.

(ii) If the field application stresses are not known, a suitable average value (based on industry or historical data) can be used. Typical values for k are 1/500 to 1/2000.

Step 6. Include the field model and parameters in the test flow diagram created in step 4 to complete the ESS Model. Figure 5.2 illustrates a portion of a sample ESS test flow diagram.

Procedure A2. The objective of this procedure is to optimize the combined user/producer cost of achieving the specified reliability as calculated using Procedure A3. This is accomplished by selecting and placing RV and TC screens (with their respective strengths determined according to the methods of Procedure C) at various locations in the ESS model created in Procedure A1 and calculating the associated cost using Procedure A3. These costs and defects removed and remaining can be charted as illustrated in Figure 5.2.

Step 1. Selecting Assembly Level ESS. Usually ESS at the lowest level, i.e., part or assembly minimizes cost; however, depending on detection efficiency and the peculiarities of any particular electronic system, this may not always be the case. Use Table 4.4 as a guide in selecting the initial assembly level ESS.

Step 2. Select system level ESS as required to achieve the desired field reliability. Use Table 4.4 as a guide. Note that at system level RV should always be followed by TC to enhance the detection efficiency.

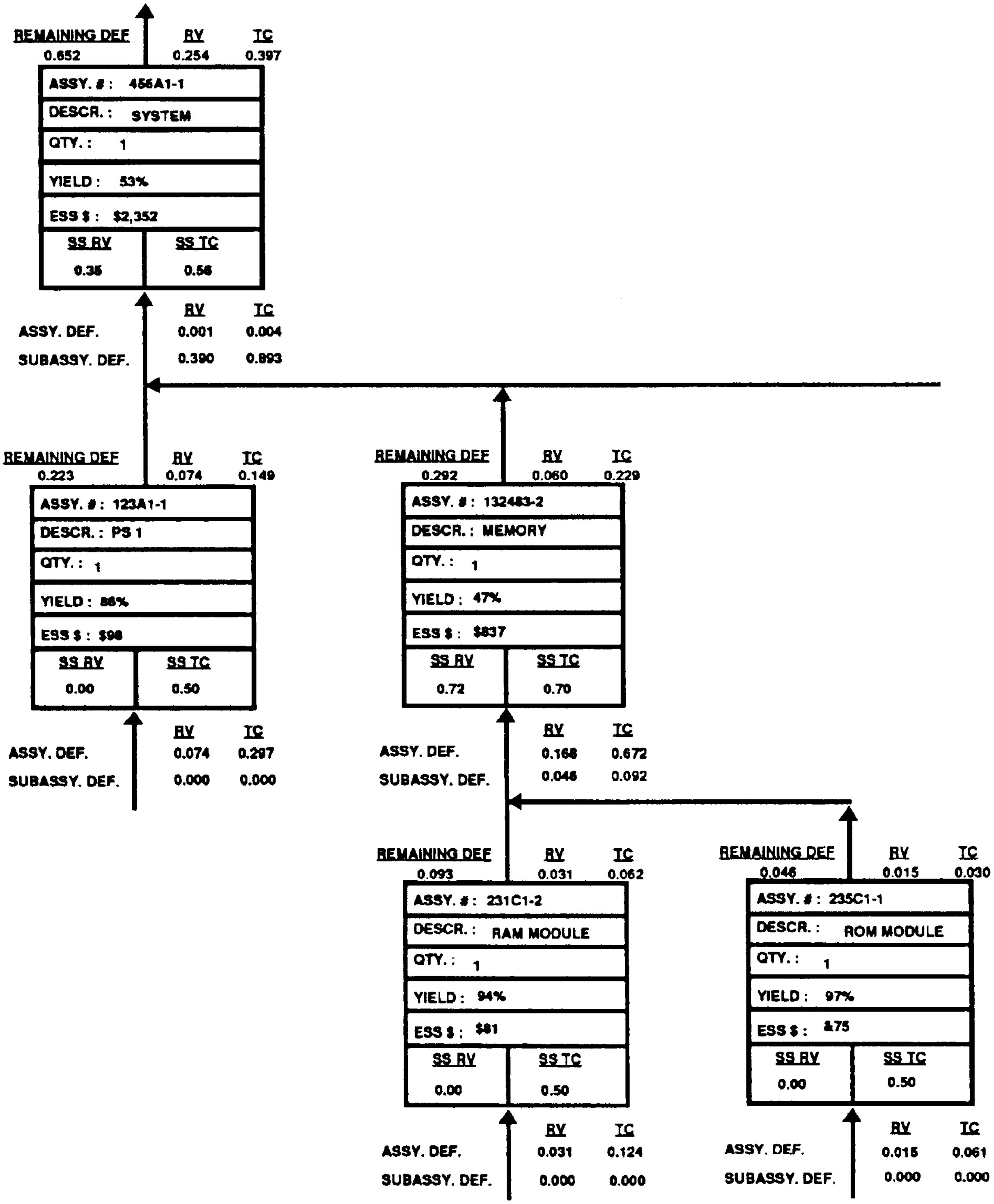
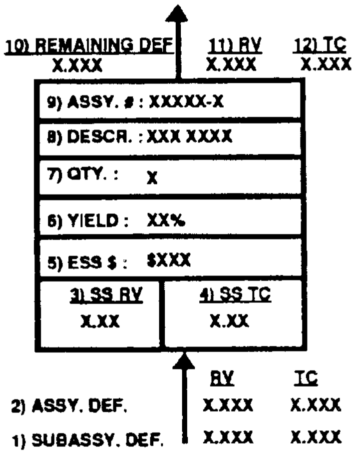


Figure 5.2: Sample ESS Test Flow Diagram



1) SUBASSY. DEF - The number of subassembly defects going into the assembly. Defects are partitioned between RV and TC. These values are determined by adding all necessary defects from every subassembly flowing directly into the assembly in question. In figure 5.2 the memory assembly (ASSY # 132483-2) has .046 RV and .092 TC subassembly defects. These values were generated by adding the RV and TC REMAINING DEF values from the RAM module (ASSY. # 231C1-2) and the ROM module (ASSY. # 235C1-1).

2) ASSY DEF. - The number of assembly defects as determined by step 1 of procedure A1. Defects are partitioned between RV and TC.

3) SS RV - Screening Strength of the Random Vibration screen as determined from Procedure C.

4) SS TC - Screening Strength of the Temperature Cycle screen as determined from Procedure C.

5) ESS $ - The cost of doing ESS for the assembly in question as determined from Procedure A3.

6) Yield - This value is determined from the equation Yield = $e^{-D_{REMOVED}}$ (ref. Appen A, equation A-7). In figure 5.2 for assy. # 235C1-1 the Yield is calculated as follows: $D_{REMOVED}$ = .076 - .046 = .03.

Yield = $e^{-.03}$ = .97 = 97%.

7) QTY - The quantity of the assembly type in question.

8) DESC. - Description of assembly.

9) ASSY # - Assembly number.

10) REMAINING DEF - The total remaining defects for the assembly in question.

11) RV (Remaining) - The remaining defects sensitive to RV determined as follows: [#1(RV) + #2(RV)] - (#3)[#1(RV) + #2(RV)].

12) TC(Remaining) - The remaining defects sensitive to TC determined as follows: [#1(TC) + #2(TC)] - (#4)[#1(TC) + #2(TC)].

Figure 5.2A: Key To Figure 5.2

Step 3. Determine the cost of this ESS plan using Procedure A3.

Step 4. Identify assemblies and modules with high system level ESS cost and for those specific assemblies select specific lower level (sub-assembly or part level) ESS. Reduce the system level SS as a result of making these changes ensuring that field reliability is achieved. Recalculate the ESS cost.

Step 5. Repeat step 4 until the program has been optimized for cost.

Procedure A3. The objective of this procedure is to determine the cost of the ESS program, defined as follows:

ESS COST = FACTORY TEST COST + FACTORY ESS COST + FACTORY REWORK COST + FIELD FAILURE COST.

Step 1. Determine the cost of factory testing. This should include all equipment costs including equipment calibration and maintenance, operation, documentation, facilities, utilities (power, water, liquid nitrogen etc.) and labor costs including those associated with performing the screen, recording results, and performing quality assurance and administrative tasks. It should be noted that some of the costs indicated will be incurred independent of ESS.

Step 2. Determine the cost of factory ESS at each stage that it is performed. Include those factors and incidental costs mentioned in step 1.

Step 3. Determine the number of defects removed at each stage of screening using $D_{REMOVED} = D_{IN} * SS$ (ref. Appendix A). This is applicable to RV and TC separately. The RV and TC faults are also shown on the test flow diagram (ref. Figure 5.2).

Step 4. Determine the average total cost to repair defects at each stage. This cost will include all fault diagnostics, rework/repair, retest, repeat ESS, and data recording costs. Include all the incidental costs incurred. These should include carrying costs for spares, additional transit time for equipment, idle time, support and administration. Also included in these incidental costs should be logistics support considerations such as the costs associated with providing spares with a minimum amount of ESS. Once corrected, a defect should not reappear. As a result, the cost of repairing a specific defect goes away. In a properly conducted ESS program the total rework/repair costs should continually go down and then become constant.

Step 5. Determine the "defect cost" by multiplying the number of defects removed at each stage by the cost to repair each defect.

Step 6. Consider the user cost by treating the field as an extension of the ESS test flow and determining the user's cost due to a defect.

Step 7. Determine the total user/producer cost for the ESS program as the sum of those costs determined in steps 1 through 6.

Procedure A4. After optimizing the screen selection and placement, it is necessary to ensure that the ESS is not too stressful and does not consume too much of the useful(fatigue) life. This is determined by calculating the damage index D from the equation $D = NS^B$ where N represents the stress duration, S = stress level, and B = fatigue exponent. The damage index should be calculated for both ESS and useful life. The life capabilities can be determined from design requirements, qualification test, or the anticipated end application.

For TC* N = number of cycles
S = temperature range in degree Celsius
B = 2.5 (thermal fatigue exponent for solder)

For RV*
N = duration of vibration (hours or minutes)
S = Grms vibration level
B = 6.4 (vibration fatigue exponent for solder)

An example of a fatigue life calculation follows.

Temperature Cycling [B = 2.5]

	Life(L)	ESS(E)
N = No. of Cycles	$N_L = 7300$	$N_E = 50$
S = Temperature Range	$S_L = 30$	$S_E = 120$
B = Thermal Fatigue Exponent	$B_L = 2.5$	$B_E = 2.5$
	$D_L = N_L S_L^{B_L}$	$D_E = N_E S_E^{B_E}$
	$D_L = (7300)(30)^{2.5}$	$D_E = (50)(120)^{2.5}$
	$D_L = 35{,}985{,}372$	$D_E = 7{,}887{,}205$

$$\%\text{ of useful life consumed by ESS} = \frac{D_E}{D_L} = 21.9\%$$

Random Vibration [B = 6.4]

	Life(L)	ESS(E)
N = Duration (Min.)	$N_L = 2 \times 10^6$	$N_E = 5$
S = Level (Grms)	$S_L = 1$	$S_E = 6$
B = Vibration Fatigue Exponent	$B_L = 6.4$	$B_E = 6.4$
	$D_L = N_L S_L^{B_L}$	$D_E = N_E S_E^{B_E}$
	$D_L = (2 \times 10^6)(1)^{6.4}$	$D_E = (5)(6)^{6.4}$
	$D_L = 2{,}000{,}000$	$D_E = 477{,}681$

$$\%\text{ of useful life consumed by ESS} = \frac{D_E}{D_L} = 23.8\%$$

The allowable percentage of useful life consumed by ESS is dependent on the particular application. The procedure described may require modifications based on individual design specifics and/or susceptibilities. Care should be taken when using the damage index. The index may be misleading for short term life items.

*REF Crandall - Random Vibration, publisher - John Wiley and Sons, NY
Engelmaier - Effects of Power Cycling in LCC, publisher - Bell Laboratories, NJ

Procedure A5. Refine the program as designed using A1 through A4 by determining actual values for D_{IN}, SS, DE, PE, and SAF from factory and field data analyzed using Procedure D. The development or early preproduction phase should be used to verify and/or refine the original estimates. Subsequently, the production data should be analyzed on a regular basis to ensure the program remains optimum under changing conditions.

5.3 Procedure B - Estimating Defect Density.

5.3.1 Objective. Obtain estimates of the number of defects resident in the system prior to beginning ESS.

5.3.2 Methodology. Various imperfections are introduced during the assembly and integration of the equipment due to state of the art limitations in the design, testing, and manufacturing of parts and assemblies. The total number of imperfections is dependent upon the quantity and quality (technology, screening, reliability level, etc.) of the parts used and the assembly complexity (number of connections, processing, packaging densities, etc.). Unless removed through factory ESS some fraction of these imperfections will precipitate under field stress conditions and cause equipment failure. The number of imperfections that will precipitate is dependent upon the factors mentioned above and the field stress levels. The number of defects for either factory ESS or field must therefore be defined relative to the applicable factory and field stress levels.

In this procedure the number of defects is defined relative to a baseline stress level equivalent to R&M 2000 ESS guidelines. Appropriate factors are then applied to determine the number of defects for different stress levels of vibration, temperature and temperature transition rates that occur in the factory and field. It is important to address the stress adjustment factors when planning an ESS program since they affect the economic optimization. Increasing ESS stress levels causes more defects to precipitate (than would normally occur in the field), incurring added rework and retest cost. Reducing ESS stress levels increases the time required to remove field defects thereby affecting throughput and equipment utilization, etc. Note that factory ESS stress levels should always be higher than the application stresses.

To ensure that the ESS program has an appropriate balance of RV and TC stresses, the estimated defects must be divided in groups.

- RV defects (i.e., those defects that can be precipitated by RV stress only)
- TC defects (i.e., those defects that can be precipitated by TC stress only)
- R-TC defects, (i.e. those defects that can be precipitated by either TC or RV stress)
- Time-Temperature - Humidity - Bias (TTHB) defects, (i.e., those defects precipitated by a combination of time, temperature, humidity, and electrical bias)
- Mechanical Shock (MS), (i.e., those defects precipitated by mechanical shock).

Factory ESS is effective in removing RV, MS, and TC sensitive defects with the majority of TTHB sensitive defects escaping to the field. Field defects thus comprise residual RV and TC defects approaching a constant failure rate distribution (i.e., the screening limit). TTHB defects have a different time to failure distribution than TC or RV defects and for practical purposes are considered non-screenable and are not addressed by this ESS program.

The procedure steps are as follows:

i) Estimate defects for each assembly and the total system at baseline stress.

ii) Proportion the defects into RV and TC sensitive populations.

iii) Apply stress adjustment factors to determine the defects under different factory stress levels.

The initial estimates derived using these procedures are only approximate and should be refined based on the user's actual data obtained during the development phase or from the production of similar equipment. Adjustment may be required on a system or individual assembly basis. The procedures for refining the original estimate are provided in Procedure D.

5.3.3 Procedure steps.

Procedure B1. Determine the number of latent defects resident in the equipment at baseline stress as follows:

Step 1. The equipment to be screened should be depicted in chart form down to the assembly level as illustrated in Figures 5.3 and 5.4. The procedure uses a three-level equipment breakdown structure, i.e. System, Unit and Assembly, to illustrate the methodology for planning a stress screening program. Other equipment breakdown structures are, of course, possible and can be adapted to the structure used herein. Figure 5.3 shows the breakdown of a system to be screened into three units. Figure 5.4 shows the breakdown of one of the units into its constituent assemblies.

Step 2. The number of defects in a system depends on the quantity and quality of parts and workmanship characteristics. Therefore it is necessary to determine the system complexity which is described by a complexity matrix. This matrix comprises the individual complexity vectors for each assembly and sub-assembly, including appropriate factors for multi-use assemblies. These complexity vectors are defined by the quantity of parts used in various part-type reliability categories and the quantity of manufacturing (assembly and soldering) characteristics present as defined in MIL-STD-2000. A sample assembly complexity vector is shown in Figure 5.5. An assembly complexity vector should be developed for each assembly depicted in the unit breakdown charts developed in step 1. Figure 5.5 and the template in Figure 5.6 can aid in constructing the assembly complexity vectors. A system complexity matrix should then be developed by combining all assembly complexity vector values. A sample system complexity matrix is shown in figure 5.7. The key to the figure can help to construct the system complexity matrix. Figure 5.8 provides a template for the system complexity matrix.

Step 3. Determine the initial number of defects at baseline stress by multiplying the system complexity matrix by the baseline stress defect density vector. The baseline stress defect density vector is determined from Table 5.1 or from prior industry and user data.

Step 4. Proportion the total defects into populations that are sensitive to RV and TC. This improves the modeling accuracy and ensures a suitable balance of RV and TC is achieved. Studies indicate that typically 20% of the total defects are sensitive to RV and 80% to TC (reference 4.4.1.1).

NOTE: The population of RV and TC defects is based on the total population and not the factory fallout. Some factory fallout is affected by the relative RV and TC screening strengths.

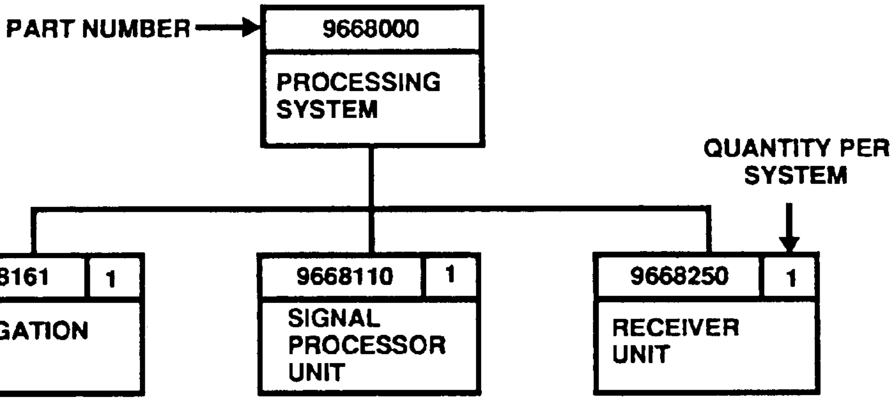


Figure 5.3: System Breakdown Chart

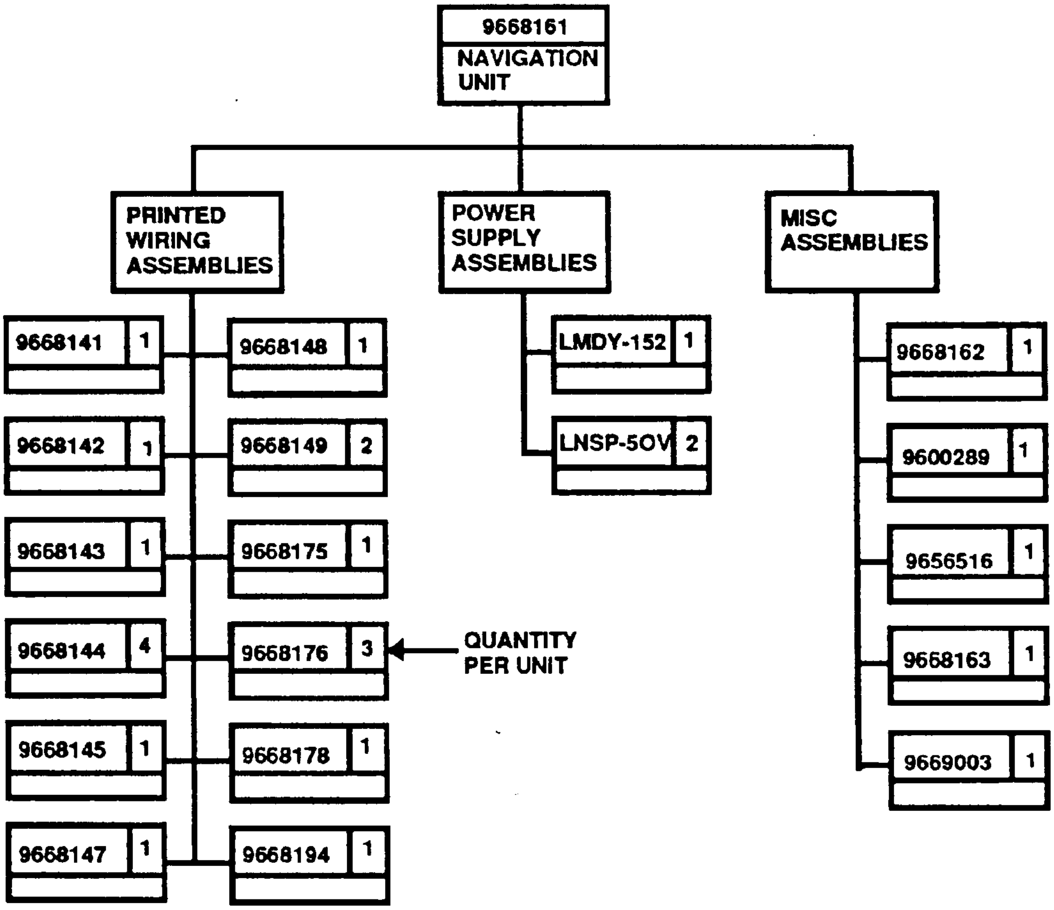


Figure 5.4: Unit Breakdown To Assembly Level

ASSY. # 149C3 - 3 ①	QTY/NEXT ASSY.: 1 ④	SCREEN #: 3 ⑦
DESCRIPTION:PWR SUPPLY ②	RV DE: 0.5 ⑤	TC DE: 0.5 ⑧
USED ON: 456A1-1 ③	TEST $: $50.00 ⑥	REWORK $: $100.00 ⑨

⑩ PART TYPE — GRADE/QUANTITY

PART TYPE	S	B	B-1
MICROCIRCUITS	0	35	61

PART TYPE	JANTXV	JANTX	JAN	LOWER	PLASTIC
TRANSISTORS	46	0	15	0	0
DIODES	120	0	22	0	0

PART TYPE	S	R	P	M	L	MIL-SPEC	LOWER
RESISTORS	0	0	277	0	0	3	0
CAPACITORS	0	0	118	0	0	14	0

PART TYPE	MIL-SPEC	LOWER
INDUCTORS	0	12
RELAYS	3	0
SWITCHES	0	0
CONNECTORS	5	0
PWBs	1	0

PART TYPE	ALL
ROTATING DEVICES	0

TOTAL SOLDER CONNECTIONS: 2806 ⑪

TOTAL # OF PARTS: 732 ⑫

TOTAL # OF LEADS: 3000 ⑬

TOTAL # OF TERMINALS: 2 ⑭

TOTAL # OF WIRE CONNECTIONS: 7 ⑮

TOTAL # OF PWAs: 1 ⑯

TOTAL # OF ASSEMBLIES: 3742 ⑰

TOTAL # OF ASSEMBLIES = # OF PARTS + # OF LEADS + # OF TERMINALS + # OF WIRES + # OF PWBs

Notes:

1. Descriptive number of the assembly.
2. Description of the assembly.
3. Descriptive number of the next higher level unit that the assembly is used on.
4. The quantity of this type of assembly that is used on the next higher level unit.
5. Random Vibration Detection Efficiency as determined from Procedure C.
6. Test cost as determined from Procedure A.
7. The number assigned to the screen for this assembly.
8. Temperature Cycling Detection Efficiency as determined from Procedure C.
9. The estimated cost of rework as determined from Procedure A.
10. A listing of the quantity of all part types by quality grade.
11. DOD-STD-2000 solder normalizing number, calculated from the number of component leads + connector pins + wire connections.
12. Total number of all parts, added from block 10.
13. Total number of leads - includes all microcircuit pins and other part leads. For leadless chips use the number of solder bumps.
14. The total number of terminals.
15. The total number of wiring connections.
16. The total number of PWBs.
17. The total number of assemblies calculated as shown below block 17.

Figure 5.5: Sample Assembly Complexity Vector

ASSY. #	QTY/NEXT ASSY.:	SCREEN #:
DESCRIPTION:	RV DE:	TC DE:
USED ON:	TEST $:	REWORK $:

PART TYPE GRADE/QUANTITY

	S	B	B-1
MICROCIRCUITS			

	JANTXV	JANTX	JAN	LOWER	PLASTIC
TRANSISTORS					
DIODES					

	S	R	P	M	L	MIL-SPEC	LOWER
RESISTORS							
CAPACITORS							

	MIL-SPEC	LOWER
INDUCTORS		
RELAYS		
SWITCHES		
CONNECTORS		
PWBs		

	ALL
ROTATING DEVICES	

TOTAL SOLDER CONNECTIONS:	TOTAL # OF ASSEMBLIES:
TOTAL # OF PARTS:	TOTAL # OF ASSEMBLIES = # OF PARTS + # OF LEADS + # OF TERMINALS + # OF WIRES + # OF PWBs
TOTAL # OF LEADS:	
TOTAL # OF TERMINALS:	
TOTAL # OF WIRE CONNECTIONS:	
TOTAL # OF PWAs:	

Figure 5.6: Template To Create Assembly Complexity Vector

EQUIPT: EXAMPLE ①	ASSY DEF: 1.124 ②	PART DEF: 0.806 ③	WRK DEF 0.318 ④
ENVIRON.: AIF ⑤	ESS $: $1,000 ⑥	DEF REMVD: 0.00 ⑦	DEF REMN: 1.1236 ⑧

⑨ PART TYPE — GRADE/QUANTITY

PART TYPE	S	B	B-1
MICROCIRCUITS	0	284	261

	JANTXV	JANTX	JAN	LOWER	PLASTIC
TRANSISTORS	174	0	118	0	0
DIODES	374	0	40	0	0

	S	R	P	M	L	MIL-SPEC	LOWER
RESISTORS	0	0	1265	0	0	31	0
CAPACITORS	0	0	696	0	0	24	0

	MIL-SPEC	LOWER
INDUCTORS	5	17
RELAYS	12	0
SWITCHES	0	0
CONNECTORS	31	0
PWBs	7	0

	ALL
ROTATING DEVICES	0

TOTAL SOLDER CONNECTIONS: 2806 ⑩

TOTAL # OF PARTS: 732 ⑪

TOTAL # OF LEADS: 3000 ⑫

TOTAL # OF TERMINALS: 2 ⑬

TOTAL # OF WIRE CONNECTIONS: 7 ⑭

TOTAL # OF PWAs: 1 ⑮

TOTAL # OF ASSEMBLIES: 3742 ⑯

TOTAL # OF ASSEMBLIES = # OF PARTS + # OF LEADS + # OF TERMINALS + # OF WIRES + # OF PWBs

TOTAL WRK: 6548 ⑰

Notes:

1. Description of the equipment.
2. Sum of the defects on each assembly referenced to the specified environment excluding the SAF. This sum does not include multiple usages of an assembly and thus is not necessarily the total defects per system.
3. The portion of ASSY defects due to parts.
4. The portion of ASSY Def due to workmanship causes.
5. The environment specified for the system in question.
6. Cost of ESS calculated as defects removed x rework cost + test cost + environmental exposure cost.
7. Total defects removed, including SAF effect and multiple usage assemblies. This is the total factory ESS fallout.
8. Remaining defects after completion of ESS relative to the specified environment excluding SAF.
9. A listing of the quantity of all part types by grade.
10. Total number of solder connections in the system.
11. Sum of the quantities of each part type.
12. Total number of leads in the system.
13. Total number of terminals in the system.
14. Total number of wire connections in the system.
15. Total number of PWAs in the system.
16. Total number of assemblies calculated as shown below block 16.
17. The total work which equals ASSY# + SOLDER #.(Block 16 + Block 10).

Figure 5.7: Sample System Complexity Matrix

EQUIPT:	ASSY DEF:	PART DEF:	WRK DEF:
ENVIR. :	ESS $:	DEF REMVD:	DEF REMN :

PART TYPE GRADE/QUANTITY

	S	B	B-1
MICROCIRCUITS			

	JANTXV	JANTX	JAN	LOWER	PLASTIC
TRANSISTORS					
DIODES					

	S	R	P	M	L	MIL-SPEC	LOWER
RESISTORS							
CAPACITORS							

	MIL-SPEC	LOWER
INDUCTORS		
RELAYS		
SWITCHES		
CONNECTORS		
PWBs		

	ALL
ROTATING DEVICES	

TOTAL SOLDER CONNECTIONS:	TOTAL # OF ASSEMBLIES:
TOTAL # OF PARTS:	TOTAL # OF ASSEMBLIES = # OF PARTS + # OF LEADS + # OF TERMINALS + # OF WIRES + # OF PWBs
TOTAL # OF LEADS:	
TOTAL # OF TERMINALS:	
TOTAL # OF WIRE CONNECTIONS:	TOTAL WRK:
TOTAL # OF PWAs:	

Figure 5.8: Template to Create System Complexity Matrix

Table 5.1: Baseline Stress Defect Density Vectors (PPM)

MICROELECTRONICS DEVICES		
S	B	B-1
104.85	209.7	419.25

TRANSISTORS					RELAYS		SWITCHES	
JANTXV	JANTX	JAN	LOWER	PLASTIC	MIL	LOWER	MIL	LOWER
312.3	624.6	3,123.0	15,615.0	31,229.85	7,397.4	21,662.1	62.25	1,119.3

DIODES					ROTATING DEVICES	CONNECTORS	
JANTXV	JANTX	JAN	LOWER	PLASTIC	ALL	MIL	LOWER
64.2	128.55	642.75	3,213.45	6,426.9	124,561.8	2,089.65	4,139.4

RESISTORS						PWBs	
S	R	P	M	MIL	LOWER	MIL	LOWER
8.1	26.85	80.7	269.25	1,346.1	4,038.3	9,209.4	92,094.45

CAPACITORS							INDUCTORS	
S	R	P	M	L	MIL	LOWER	MIL	LOWER
12.45	41.52	124.53	415.11	1,245.36	1,245.36	4,151.25	1,693.02	5,643.45

ASSEMBLY CHARACTERISTICS	SOLDER CHARACTERISTICS
ALL	ALL
25	5

Note: This table was developed for the study documented in RL-TR-91-300, Vol 1.

Procedure B2. Determine the stress adjustment factor relating defects at factory (baseline stress) levels to defects at the field application stress levels as follows:

Step 1. Use tables 5.2 through 5.13 to determine the defect density vector at the anticipated field stress level. These tables represent the defect density for different application environments and were derived from field data. For factory ESS planning purposes, these tables should be rescaled to also include the defects removed by factory screening. A factor of 1.5 is typical. Multiply the system complexity matrix from Procedure B1 step 2 by the field stress defect density vector to determine the initial number of defects at the anticipated field stress levels.

Step 2. Determine the field stress adjustment factor as the ratio of the number of defects at the field stress level to the number of defects at the baseline stress level (from Procedure B1).

Step 3. If factory stress levels do not conform to the base line stress levels (defined as 6 Grms and 6 degrees C/min) apply a suitable factory stress adjustment factor (SAF) as follows:

For RV: $SAF = \left(\frac{\text{Actual Grms}}{\text{6 Grms}}\right)^n$ n is typically 0.5 to 1.0

For TC: $SAF = \left(\frac{\text{Actual Transition Rate}}{\text{6 Degrees C/min}}\right)^n$ n is typically 0 to 0.5

Table 5.2: Microelectronic Devices Defect Density (in PPM) for Various Environments

	QUALITY LEVEL		
ENVIRONMENT	S	B	B-1
GB	9.2	18.3	36.2
GF	19.4	38.7	77.4
GM	26.6	53.2	106.3
NS	26.6	53.1	106.3
NU	36.0	72.1	144.1
AIC	24.2	48.3	96.6
AIF	31.4	62.8	125.6
AUC	30.6	61.1	122.3
AUF	43.4	86.9	173.7
ARW	48.2	96.4	192.9
SF	11.7	23.3	46.6
MF	29.7	59.4	118.8
ML	65.1	130.2	260.3
CL	1,065.9	2,131.8	4,263.7

Table 5.3: Transistor Devices Defect Density (in PPM) for Various Environments

	QUALITY LEVEL				
ENVIRONMENT	JANTXV	JANTX	JAN	LOWER	PLASTIC
GB	10.9	21.9	109.3	546.6	1,093.2
GF	34.6	69.2	346.0	1,730.2	3,460.4
GM	82.0	160.0	799.8	3,998.8	7,997.5
NS	54.3	108.7	543.3	2,716.5	5,433.1
NU	104.6	209.3	1,046.3	5,231.7	10,463.4
AIC	103.8	207.6	1,038.1	5,190.6	10,381.2
AIF	154.0	307.9	1,539.5	7,698.0	15,395.1
AUC	170.4	340.8	1,703.9	8,519.5	17,038.9
AUF	252.6	505.2	2,528.9	12,629.3	25,258.5
ARW	139.2	278.3	1,391.6	6,957.8	13,915.6
SF	8.0	15.9	79.7	398.6	797.3
MF	252.6	505.2	775.1	3,875.5	7,751.0
ML	195.9	391.8	1,958.7	9,739.5	19,587.0
CL	3,408.9	6,817.7	34,088.7	170,443.3	340,886.7

Table 5.4: Diode Part Devices Defect Density (In PPM) for Various Environments

	QUALITY LEVEL				
ENVIRONMENT	JANTXV	JANTX	JAN	LOWER	PLASTIC
GB	5.9	11.8	59.2	296.2	592.3
GF	8.6	17.2	86.0	430.0	860.0
GM	18.9	37.7	188.5	942.3	1,884.6
NS	9.4	18.9	94.3	471.5	943.1
NU	23.5	46.9	234.6	1,173.1	2,346.2
AIC	25.0	50.0	250.0	1,250.0	2,500.0
AIF	32.7	65.4	327.0	1,634.6	3,269.3
AUC	37.33	74.6	373.1	1,865.4	3,730.8
AUF	46.55	93.05	465.4	2,327.0	4,653.9
ARW	29.9	59.8	299.2	1,496.2	2,992.3
SF	5.9	11.8	59.2	296.2	592.3
MF	18.4	36.8	183.9	919.2	1,838.5
ML	40.5	81.1	405.4	2,026.9	4,053.9
CL	641.1	1,283.8	6,419.2	32,096.2	64,192.3

Table 5.5: Resistor Devices Defect Density (In PPM) for Various Environments

	QUALITY LEVEL					
ENVIRONMENT	S	R	P	M	MIL-SPEC	LOWER
GB	0.4	1.2	3.7	12.3	61.4	184.2
GF	0.6	2.0	6.1	20.3	101.7	305.2
GM	1.6	5.4	16.3	54.4	271.8	815.5
NS	1.0	3.3	9.7	32.2	160.9	482.6
NU	2.7	8.9	26.7	89.1	445.8	1,337.3
AIC	0.9	3.0	8.9	29.6	147.8	443.6
AIF	1.5	5.0	14.9	49.8	248.8	746.3
AUC	1.8	6.1	18.4	61.3	306.4	919.0
AUF	3.3	10.8	32.2	107.4	537.0	1,611.2
ARW	3.5	11.6	34.8	116.1	580.3	1,740.9
SF	0.3	0.9	2.6	8.8	44.1	132.3
MF	2.0	6.7	20.0	66.8	333.8	1,001.5
ML	5.1	16.8	50.4	168.0	839.8	2,519.0
CL	88.4	294.7	884.1	2,947.0	14,735.0	44,205.0

Table 5.6: Capacitor Defect Density (In PPM) for Various Environments

	QUALITY LEVEL						
ENVIRONMENT	S	R	P	M	L	MIL-SPEC	LOWER
GB	1.2	3.8	11.5	38.4	115.3	115.3	384.4
GF	1.8	6.2	18.4	61.5	184.5	184.5	615.0
GM	10.9	36.2	108.4	361.3	1,083.9	1,083.9	3,613.1
NS	6.1	20.2	60.6	201.8	605.4	605.4	2,018.0
NU	17.8	59.5	178.4	594.5	1,783.5	1,783.5	5,945.0
AIC	4.3	14.1	42.3	140.9	422.8	422.8	1,409.4
AIF	5.2	17.3	51.9	173.0	518.9	518.9	1,729.2
AUC	9.8	32.6	98.0	326.7	980.1	980.1	3,267.2
AUF	13.3	44.2	132.6	442.1	1,326.1	1,326.1	4,420.0
ARW	27.7	92.2	276.7	922.5	2,767.5	2,767.5	9,225.0
SF	0.9	3.1	9.2	30.7	92.2	92.2	307.5
MF	15.0	50.0	149.9	499.7	1,499.1	1,499.1	4,996.9
ML	39.2	130.7	392.1	1,306.9	3,920.6	3,920.6	13,068.6
CL	703.1	2,344.7	7,034.1	23,446.9	70,340.6	70,340.6	234,468.6

Table 5.7: Inductor Defect Density (In PPM) for Various Environments

	QUALITY LEVEL	
ENVIRONMENT	MIL-SPEC	LOWER
GB	537.2	1,790.7
GF	1,222.9	4,076.4
GM	2,069.1	6,897.0
NS	1,179.2	3,930.5
NU	2,725.6	9,085.3
AIC	1,193.7	3,979.1
AIF	1,485.6	4,951.8
AUC	1,388.2	4,627.5
AUF	1,388.2	4,627.5
ARW	3,892.7	12,975.8
SF	537.2	1,790.7
MF	2,287.9	7,626.4
ML	5,351.7	17,838.9
CL	89,385.3	297,951.1

Table 5.8: Rotating Devices Defect Density (In PPM) for Various Environments

ENVIRONMENT	FRACTION DEFECTIVE
GB	5,935.2
GF	11,663.1
GM	29,067.0
NS	15,628.5
NU	38,980.6
AIC	14,013.0
AIF	18,602.6
AUC	17,684.7
AUF	21,907.2
ARW	56,604.8
SF	5,935.2
MF	27,965.5
ML	78,635.2
CL	N/A

Table 5.9: Relay Defect Density (In PPM) for Various Environments

	QUALITY LEVEL	
ENVIRONMENT	MIL-SPEC	LOWER
GB	142.5	210.9
GF	231.4	388.8
GM	1,073.0	3,084.4
NS	621.4	1,716.0
NU	1,898.5	5,410.3
AIC	564.3	1,089.0
AIF	627.7	1,442.4
AUC	803.8	2,012.5
AUF	929.3	2,640.0
ARW	3,221.2	9,652.3
SF	142.5	210.9
MF	1,784.5	5,034.3
ML	4,623.7	13,757.3
CL	N/A	N/A

Table 5.10: Switch Defect Density (in PPM) for Various Environments

	QUALITY LEVEL	
ENVIRONMENT	MIL-SPEC	LOWER
GB	1.4	24.4
GF	2.4	44.0
GM	10.8	194.5
NS	5.3	95.5
NU	17.2	309.7
AIC	6.7	120.7
AIF	10.8	194.6
AUC	8.4	151.6
AUF	13.7	246.1
ARW	27.1	488.4
SF	1.4	24.4
MF	15.1	271.9
ML	39.2	705.0
CL	688.3	12,388.6

Table 5.11: Connector Defect Density (in PPM) for Various Environments

	QUALITY LEVEL	
ENVIRONMENT	MIL-SPEC	LOWER
GB	73.7	97.3
GF	83.3	248.1
GM	422.8	1,016.2
NS	248.1	476.6
NU	654.9	1,298.9
AIC	175.9	576.3
AIF	274.0	851.2
AUC	387.9	811.9
AUF	603.9	1,204.6
ARW	921.9	1,770.1
SF	73.7	97.3
MF	509.6	992.6
ML	1,298.9	2,571.2
CL	23,115.8	45,733.8

Table 5.12: PWB Defect Density (In PPM) for Various Environments

	QUALITY LEVEL	
ENVIRONMENT	MIL-SPEC	LOWER
GB	425.0	4,250.0
GF	690.3	6,903.2
GM	1,710.8	17,107.9
NS	1,180.2	11,801.5
NU	2,874.1	28,741.2
AIC	1,241.4	12,413.7
AIF	1,914.9	19,148.8
AUC	3,452.4	34,523.9
AUF	5,833.5	58,334.9
ARW	4,098.7	40,986.9
SF	425.0	4,250.0
MF	2,333.3	23,332.8
ML	5,833.5	58,335.0
CL	102,267.9	N/A

Table 5.13: Manufacturing Characteristics (In PPM) In Various Environments

	MANUFACTURING CHARACTERISTICS	
ENVIRONMENT	ASSEMBLY	SOLDER
GB	0.98	1.25
GF	0.98	1.25
GM	4.90	6.27
NS	2.45	3.14
NU	7.19	9.20
AIC	2.94	3.76
AIF	3.92	5.02
AUC	3.59	4.60
AUF	5.39	6.90
ARW	10.78	13.79
SF	0.98	1.25
MF	5.88	7.53
ML	15.69	20.06
CL	274.51	351.04

5.4 Procedure C - Estimating Screening Strength

5.4.1 Objective. Estimate the number of flaws precipitated and detected (removed) by ESS.

5.4.2 Methodology. The screening strength is characterized by a precipitation term and a detection term and determines the fraction of existing flaws that are removed by ESS. The precipitation and detection terms are estimated separately and it is their product that determines the screening strength.

Precipitation is defined as the conversion of flaws with some residual strength (latent defect) into a flaw with no strength (patent defect) - for example the propagation of a crack through a wire until the wire is broken. The application of stress precipitates a certain fraction of the existing flaws. This fraction is assumed to be constant for a specified stress level and duration and the mathematics are discussed in more detail in Appendix A. A previous study ref. RADC-TR-86-149 has determined the precipitation effectiveness of various stress types and has developed mathematical expressions for each. These expressions and representative tables are provided in Tables 5.14 to 5.17. As in the estimation of initial defects, the original estimate based on these tables is only approximate and must be validated or refined based on actual user's data.

Precipitation by itself does not ensure that flaws can be detected. In many instances a concurrent stress may be required to detect and isolate the failure. For example, a broken wire may make intermittent contact at low, ambient stresses. Also, depending upon the function affected, the defect may only cause degraded performance. Either condition could require extended testing and may require concurrent stress. The capability of detecting a patent defect is measured by the detection efficiency.

The removal of a potential defect or flaw requires the flaw to be precipitated and subsequently detected and removed. The detection efficiency is defined as the capability of detecting, isolating and removing the defect once it has precipitated. It is a measure of the extent that factory testing exercises all possible field applications and conditions and is the product of the following factors and considerations:

(a) Probability of observing functional and parametric defects (i.e., probability of detection x probability of occurrence)

(b) Necessity for concurrent stress

(c) Probability of isolating and then removing the defect without creating an additional defect(s)

Studies indicate that a large fraction of defects require concurrent stress to be detectable. Therefore ESS that does not employ testing during stress application is relatively ineffective. It is also the reason why RV stress should be followed by TC. RV is relatively short in duration, thus the detection efficiency, which has a Poisson $(1 - e^{-kt})$ distribution, may be inadequate.

5.4.3 Procedure Steps

Step 1. Determine the precipitation efficiency. Expressed as a function of stress duration, the precipitation efficiency is given by 1-exp (-kt) where t is the stress duration in hours, cycles, etc. and k is a stress constant determined for each type of stress according to the following formulae:

Temperature Cycling $k = 0.0017 (\Delta T + .6)^{.6} [\ln(RATE + 2.718)]^3$

where: $\Delta T = T_{max} - T_{min}$ in degrees C ,RATE = degrees C/minute and t = # of cycles

Constant Temperature $k = 0.0017t(\Delta T + .6)^{.6}$

where : ΔT = degrees C, and t = hours

Random Vibration $k = 0.0046\, G^{1.71}$

Swept Sine Vibration	$k = 0.000727G^{0.863}$
Fixed Sine Vibration	$k = 0.00047\ G^{0.49}$

Note: All G values are in units of Grms (Source of formulae: RADC-TR-86-14)

Tables 5.14 to 5.17 provide examples of precipitation efficiency for various screening parameters. For RV screens it is necessary to include an axis sensitivity factor. RV applied in the axis perpendicular to the plane of the board will have the greatest effect. When selecting and modeling RV stress, the precipitation efficiency is thus given by [1 - exp (-kt)]* AXIS SENSITIVITY FACTOR where the axis sensitivity factor is the defect density component in the sensitive axis divided by the total defect density. Transmissibility and resonance effects must be considered and the frequency spectrum may need to be suitably notched to avert overstress or wear-out effects. Similarly, thermal mass and conductivities must be considered when determining TC transition rates and required dwell times. The stress levels for all these equations pertain to the equipment being screened and not the chambers, etc.

It should also be noted that the expressions and tables for precipitation efficiency are only approximate and, as in the estimation of initial defects, should be refined based upon actual users data according to the techniques of Procedure D.

Step 2. Determine the detection efficiency (DE). The DE term is sensitive to three factors and must be estimated accordingly. These three factors (and their respective range of values) are:

a)	Type of testing performed:	
	Functional only	0.5 to 0.8
	Functional and parametric	0.8 to 1.0
b)	Environmental conditions during test:	
	Testing performed under ambient conditions only	0.2 to 0.6
	Testing performed concurrently with stress	1.0
c)	The ability to observe and isolate the defect and the probability of successfully removing the defect without introducing another	0.8 to 1.0

The product of these factors is the detection efficiency.

Step 3. Determine the screening strength as the product of the precipitation efficiency and detection efficiency.

EXAMPLE OF SS CALCULATION

For TC of 4 cycles at 5°C/minute over a 100°C range, PE = .6027 (from Table 5.15)

For RV of 5 minutes at 5 Grms, PE = .303 (From Table 5.14)

Given the following "DE" factors	Functional and parametric Test	.9
	Test during environmental stress	1
	Probability of detecting, isolating and removing the defect	.95

The detection efficiency is $0.9 \times 1.0 \times .95 = .855$

SS (TC) = PE x DE = .6027 * .855 = 0.5153
SS (RV) = PE x DE = .303 * .855 = 0.2

Table 5.14: Precipitation Efficiency Factors - Random Vibration Screens

DURATION (MINUTES)	ACCELERATION LEVEL (G - RMS)																			
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
5	0.007	0.023	0.045	0.072	0.104	0.140	0.178	0.218	0.260	0.303	0.346	0.389	0.431	0.473	0.514	0.553	0.591	0.627	0.661	0.693
10	0.014	0.045	0.088	0.140	0.198	0.260	0.324	0.389	0.452	0.514	0.572	0.627	0.677	0.723	0.764	0.800	0.832	0.861	0.885	0.906
15	0.021	0.067	0.129	0.202	0.282	0.363	0.444	0.522	0.595	0.661	0.720	0.772	0.816	0.854	0.885	0.911	0.931	0.948	0.961	0.971
20	0.028	0.088	0.168	0.260	0.356	0.452	0.543	0.626	0.700	0.764	0.817	0.861	0.896	0.923	0.944	0.960	0.972	0.981	0.987	0.991
25	0.035	0.109	0.206	0.314	0.424	0.529	0.625	0.708	0.778	0.835	0.880	0.915	0.941	0.959	0.973	0.982	0.989	0.993	0.995	0.997
30	0.041	0.129	0.241	0.363	0.484	0.595	0.691	0.772	0.836	0.885	0.922	0.948	0.966	0.979	0.987	0.992	0.995	0.997	0.998	0.999
35	0.048	0.149	0.275	0.409	0.538	0.651	0.746	0.822	0.878	0.920	0.949	0.968	0.981	0.989	0.994	0.996	0.998	0.999	0.999	1.000
40	0.055	0.168	0.308	0.452	0.586	0.700	0.791	0.860	0.910	0.944	0.966	0.981	0.989	0.994	0.997	0.998	0.999	1.000	1.000	1.000
45	0.061	0.187	0.339	0.492	0.629	0.742	0.829	0.891	0.933	0.961	0.978	0.988	0.994	0.997	0.998	0.999	1.000	1.000	1.000	1.000
50	0.068	0.205	0.369	0.529	0.668	0.778	0.859	0.915	0.951	0.973	0.986	0.993	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000
55	0.074	0.224	0.397	0.563	0.702	0.809	0.884	0.933	0.964	0.981	0.991	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000
60	0.081	0.241	0.424	0.595	0.734	0.836	0.905	0.948	0.973	0.987	0.994	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
65	0.087	0.258	0.450	0.624	0.761	0.859	0.922	0.959	0.980	0.991	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
70	0.094	0.275	0.475	0.651	0.786	0.878	0.936	0.968	0.985	0.994	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
75	0.100	0.292	0.498	0.677	0.809	0.895	0.947	0.975	0.989	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
80	0.106	0.308	0.521	0.700	0.829	0.910	0.956	0.981	0.992	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
85	0.113	0.324	0.543	0.722	0.846	0.923	0.964	0.985	0.994	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
90	0.119	0.339	0.563	0.742	0.862	0.933	0.971	0.988	0.996	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
95	0.125	0.354	0.583	0.761	0.877	0.943	0.976	0.991	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	0.131	0.369	0.602	0.778	0.890	0.951	0.980	0.993	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
105	0.137	0.383	0.619	0.794	0.901	0.958	0.984	0.994	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
110	0.143	0.397	0.637	0.809	0.911	0.964	0.987	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
115	0.149	0.411	0.653	0.823	0.921	0.969	0.989	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
120	0.155	0.424	0.669	0.836	0.929	0.973	0.991	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
125	0.161	0.437	0.683	0.848	0.936	0.977	0.993	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
130	0.167	0.450	0.698	0.859	0.943	0.980	0.994	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
135	0.173	0.463	0.711	0.869	0.949	0.983	0.995	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
140	0.179	0.475	0.724	0.876	0.954	0.985	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
145	0.184	0.487	0.737	0.887	0.959	0.987	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
150	0.190	0.498	0.748	0.895	0.963	0.989	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 5.14: Precipitation Efficiency Factors - Random Vibration Screens (Continued)

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
155	0.196	0.510	0.760	0.903	0.967	0.991	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
160	0.201	0.521	0.771	0.910	0.971	0.992	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
165	0.207	0.532	0.781	0.917	0.974	0.993	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
170	0.213	0.543	0.791	0.923	0.976	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
175	0.218	0.553	0.800	0.928	0.979	0.995	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
180	0.224	0.563	0.809	0.933	0.981	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
185	0.229	0.573	0.818	0.938	0.983	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
190	0.234	0.583	0.826	0.943	0.985	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
195	0.240	0.592	0.834	0.947	0.986	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
200	0.245	0.601	0.841	0.951	0.988	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
205	0.250	0.611	0.848	0.954	0.989	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
210	0.256	0.619	0.855	0.958	0.990	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
215	0.261	0.628	0.862	0.961	0.991	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
220	0.266	0.637	0.868	0.964	0.992	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
225	0.271	0.645	0.874	0.966	0.993	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
230	0.276	0.653	0.880	0.969	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
235	0.281	0.661	0.885	0.971	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
240	0.286	0.668	0.890	0.973	0.995	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
245	0.291	0.676	0.895	0.975	0.995	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
250	0.296	0.683	0.900	0.977	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
255	0.301	0.691	0.904	0.978	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
260	0.306	0.698	0.909	0.980	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
265	0.311	0.704	0.913	0.981	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
270	0.316	0.711	0.917	0.983	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
275	0.321	0.718	0.920	0.984	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
280	0.325	0.724	0.924	0.985	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
285	0.330	0.730	0.927	0.986	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
290	0.335	0.737	0.931	0.987	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
295	0.340	0.743	0.934	0.988	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
300	0.344	0.748	0.937	0.989	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 5.14: Precipitation Efficiency Factors - Random Vibration Screens (Continued)

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
305	0.349	0.754	0.940	0.990	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
310	0.353	0.760	0.942	0.991	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
315	0.358	0.765	0.945	0.991	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
320	0.362	0.771	0.947	0.992	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
325	0.367	0.776	0.950	0.992	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
330	0.371	0.781	0.952	0.993	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
335	0.376	0.786	0.954	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
340	0.380	0.791	0.956	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
345	0.384	0.795	0.958	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
350	0.389	0.800	0.960	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
355	0.393	0.805	0.962	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
360	0.397	0.809	0.964	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
365	0.401	0.813	0.965	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
370	0.406	0.818	0.967	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
375	0.410	0.822	0.968	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
380	0.414	0.826	0.970	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
385	0.418	0.830	0.971	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
390	0.422	0.834	0.972	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
395	0.426	0.837	0.974	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
400	0.430	0.841	0.975	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
405	0.434	0.845	0.976	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
410	0.438	0.848	0.977	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
415	0.442	0.852	0.978	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
420	0.446	0.855	0.979	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
425	0.450	0.858	0.980	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
430	0.454	0.862	0.981	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
435	0.458	0.865	0.982	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
440	0.461	0.868	0.983	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
445	0.465	0.871	0.983	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
450	0.469	0.874	0.984	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 5.14: Precipitation Efficiency Factors - Random Vibration Screens (Continued)

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.0	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
455	0.473	0.877	0.985	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
460	0.476	0.879	0.985	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
465	0.480	0.882	0.986	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
470	0.484	0.885	0.987	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
475	0.487	0.888	0.987	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
480	0.491	0.890	0.988	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
485	0.494	0.893	0.988	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
490	0.498	0.895	0.989	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
495	0.501	0.897	0.989	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
500	0.505	0.900	0.990	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
505	0.508	0.902	0.990	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
510	0.512	0.904	0.991	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
515	0.515	0.906	0.991	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
520	0.519	0.909	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
525	0.522	0.911	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
530	0.525	0.913	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
535	0.529	0.915	0.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
540	0.532	0.917	0.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
545	0.535	0.918	0.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
550	0.539	0.920	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
555	0.542	0.922	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
560	0.545	0.924	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
565	0.548	0.926	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
570	0.551	0.927	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
575	0.554	0.929	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
580	0.558	0.931	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
585	0.561	0.932	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
590	0.564	0.934	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
595	0.567	0.935	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	0.570	0.937	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 5.15: Precipitation Efficiency Factors - Temperature Cycling Screens

NUMBER OF CYCLES	TEMP. RATE OF CHANGE °C/MIN	TEMPERATURE DELTA (ΔT) - °C								
		20	40	60	80	100	120	140	160	180
2	5	.1632	.2349	.2886	.3324	.3697	.4022	.4312	.4572	.4809
2	10	.2907	.4031	.4812	.5410	.5891	.6290	.6628	.6920	.7173
2	15	.3911	.5254	.6124	.6752	.7232	.7612	.7920	.8175	.8388
2	20	.4707	.6155	.7034	.7636	.8075	.8407	.8665	.8871	.9037
2	25	.5350	.6835	.7684	.8237	.8623	.8904	.9114	.9276	.9402
2	30	.5878	.7359	.8160	.8659	.8992	.9226	.9395	.9521	.9616
4	5	.2998	.4146	.4939	.5543	.6027	.6427	.6764	.7054	.7305
4	10	.4969	.6437	.7308	.7893	.8312	.8624	.8863	.9051	.9201
4	15	.6292	.7748	.8498	.8945	.9234	.9430	.9567	.9667	.9740
4	20	.7198	.8522	.9120	.9441	.9629	.9746	.9822	.9873	.9907
4	25	.7837	.8998	.9464	.9689	.9810	.9880	.9922	.9948	.9964
4	30	.8301	.9302	.9662	.9820	.9898	.9940	.9963	.9977	.9985
6	5	.4141	.5521	.6399	.7024	.7496	.7864	.8160	.8401	.8601
6	10	.6431	.7873	.8603	.9033	.9306	.9489	.9617	.9708	.9774
6	15	.7742	.8931	.9418	.9657	.9788	.9864	.9910	.9939	.9958
6	20	.8517	.9432	.9739	.9868	.9929	.9960	.9976	.9986	.9991
6	25	.8994	.9683	.9876	.9945	.9974	.9987	.9993	.9996	.9998
6	30	.9299	.9816	.9938	.9976	.9990	.9995	.9998	.9999	.9999
8	5	.5098	.6574	.7439	.8014	.8421	.8723	.8953	.9132	.9274
8	10	.7468	.8731	.9275	.9556	.9715	.9811	.9871	.9910	.9936
8	15	.8625	.9493	.9774	.9889	.9941	.9967	.9981	.9989	.9993
8	20	.9215	.9781	.9923	.9969	.9986	.9994	.9997	.9998	.9999
8	25	.9532	.9900	.9971	.9990	.9996	.9999	.9999	1.0000	1.0000
8	30	.9711	.9951	.9989	.9997	.9999	1.0000	1.0000	1.0000	1.0000
10	5	.5898	.7378	.8178	.8674	.9005	.9237	.9405	.9529	.9623
10	10	.8204	.9242	.9624	.9796	.9883	.9930	.9956	.9972	.9982
10	15	.9163	.9759	.9912	.9964	.9984	.9992	.9996	.9998	.9999
10	20	.9585	.9916	.9977	.9993	.9997	.9999	1.0000	1.0000	1.0000
10	25	.9783	.9968	.9993	.9998	1.0000	1.0000	1.0000	1.0000	1.0000
10	30	.9881	.9987	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 5.15: Preciption Efficiency Factors - Temperature Cycling Screens (Continued)

NUMBER OF CYCLES	TEMP. RATE OF CHANGE °C/MIN	TEMPERATURE DELTA(ΔT) - °C								
		20	40	60	80	100	120	140	160	180
12	5	.6568	.7994	.8704	.9115	.9373	.9544	.9661	.9744	.9804
12	10	.8726	.9548	.9805	.9906	.9952	.9974	.9985	.9991	.9995
12	15	.9490	.9886	.9966	.9988	.9996	.9998	.9999	1.0000	1.0000
12	20	.9780	.9968	.9993	.9998	.9999	1.0000	1.0000	1.0000	1.0000
12	25	.9899	.9990	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
12	30	.9951	.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
14	5	.7128	.8465	.9078	.9409	.9605	.9727	.9807	.9861	.9898
14	10	.9096	.9730	.9899	.9957	.9980	.9990	.9995	.9997	.9999
14	15	.9690	.9946	.9987	.9996	.9999	1.0000	1.0000	1.0000	1.0000
14	20	.9884	.9988	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
14	25	.9953	.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
14	30	.9980	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
16	5	.7597	.8826	.9344	.9605	.9751	.9837	.9890	.9925	.9947
16	10	.9359	.9839	.9947	.9980	.9992	.9996	.9998	.9999	1.0000
16	15	.9811	.9974	.9995	.9999	1.0000	1.0000	1.0000	1.0000	1.0000
16	20	.9938	.9995	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
16	25	.9978	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
16	30	.9992	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
18	5	.7989	.9102	.9533	.9737	.9843	.9903	.9938	.9959	.9973
18	10	.9545	.9904	.9973	.9991	.9997	.9999	.9999	1.0000	1.0000
18	15	.9885	.9988	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
18	20	.9967	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
18	25	.9990	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
18	30	.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
20	5	.8317	.9313	.9668	.9824	.9901	.9942	.9965	.9978	.9986
20	10	.9678	.9943	.9986	.9996	.9999	1.0000	1.0000	1.0000	1.0000
20	15	.9930	.9994	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
20	20	.9983	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
20	25	.9995	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
20	30	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 5.15: Precipitation Efficiency Factors - Temperature Cycling Screens (Continued)

NUMBER OF CYCLES	TEMP. RATE OF CHANGE °C/MIN	TEMPERATURE DELTA (ΔT) - °C								
		20	40	60	80	100	120	140	160	180
22	5	.8592	.9474	.9764	.9883	.9938	.9965	.9980	.9988	.9993
22	10	.9771	.9966	.9993	.9998	.9999	1.0000	1.0000	1.0000	1.0000
22	15	.9957	.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
22	20	.9991	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
22	25	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
22	30	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
24	5	.8822	.9598	.9832	.9922	.9961	.9979	.9989	.9993	.9996
24	10	.9838	.9980	.9996	.9999	1.0000	1.0000	1.0000	1.0000	1.0000
24	15	.9974	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
24	20	.9995	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
24	25	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
24	30	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
26	5	.9014	.9692	.9880	.9948	.9975	.9988	.9993	.9996	.9998
26	10	.9885	.9988	.9998	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
26	15	.9984	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
26	20	.9997	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
26	25	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
26	30	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
28	5	.9175	.9765	.9915	.9965	.9984	.9993	.9996	.9998	.9999
28	10	.9918	.9993	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
28	15	.9990	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
28	20	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
28	25	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
28	30	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
30	5	.9310	.9820	.9939	.9977	.9990	.9996	.9998	.9999	.9999
30	10	.9942	.9996	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
30	15	.9994	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
30	20	.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
30	25	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
30	30	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 5.16: Precipitation Efficiency Factors - Swept Sine Vibration Screens

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
5	.0020	.0036	.0051	.0066	.0080	.0093	.0107	.0120	.0132	.0145	.0157	.0169	.0181	.0193	.0205	.0216	.0228	.0239	.0250	.0262
10	.0040	.0072	.0103	.0131	.0159	.0186	.0212	.0238	.0263	.0287	.0312	.0335	.0359	.0382	.0405	.0428	.0450	.0473	.0495	.0516
15	.0060	.0108	.0154	.0196	.0238	.0278	.0316	.0354	.0391	.0428	.0464	.0499	.0534	.0568	.0602	.0635	.0668	.0701	.0733	.0765
20	.0080	.0144	.0204	.0261	.0316	.0368	.0420	.0470	.0519	.0566	.0614	.0660	.0705	.0750	.0794	.0838	.0881	.0923	.0965	.1006
25	.0099	.0180	.0255	.0325	.0393	.0458	.0522	.0584	.0644	.0703	.0761	.0818	.0874	.0929	.0983	.1036	.1088	.1140	.1191	.1242
30	.0119	.0216	.0305	.0389	.0470	.0547	.0623	.0696	.0768	.0838	.0906	.0973	.1039	.1104	.1167	.1230	.1291	.1352	.1412	.1471
35	.0139	.0251	.0355	.0452	.0546	.0636	.0723	.0807	.0890	.0970	.1049	.1126	.1201	.1275	.1348	.1420	.1490	.1559	.1627	.1694
40	.0159	.0287	.0404	.0515	.0621	.0723	.0822	.0917	.1010	.1101	.1189	.1276	.1361	.1444	.1525	.1605	.1684	.1761	.1837	.1911
45	.0178	.0322	.0454	.0578	.0696	.0810	.0919	.1026	.1129	.1230	.1328	.1424	.1517	.1609	.1699	.1787	.1873	.1958	.2041	.2123
50	.0198	.0357	.0503	.0640	.0770	.0895	.1016	.1133	.1246	.1357	.1464	.1569	.1671	.1771	.1869	.1964	.2058	.2150	.2241	.2329
55	.0217	.0392	.0552	.0701	.0844	.0980	.1112	.1239	.1362	.1482	.1598	.1711	.1822	.1930	.2035	.2138	.2239	.2338	.2435	.2530
60	.0237	.0427	.0600	.0763	.0917	.1065	.1207	.1344	.1476	.1605	.1730	.1852	.1970	.2085	.2198	.2308	.2416	.2521	.2624	.2725
65	.0256	.0462	.0649	.0824	.0990	.1148	.1300	.1447	.1589	.1726	.1860	.1989	.2115	.2238	.2358	.2475	.2589	.2700	.2809	.2916
70	.0276	.0496	.0697	.0884	.1061	.1231	.1393	.1549	.1700	.1846	.1988	.2125	.2258	.2388	.2514	.2638	.2758	.2875	.2989	.3101
75	.0295	.0531	.0745	.0944	.1133	.1313	.1485	.1650	.1810	.1964	.2113	.2258	.2399	.2535	.2668	.2797	.2923	.3045	.3165	.3282
80	.0315	.0565	.0792	.1004	.1204	.1394	.1576	.1750	.1918	.2081	.2237	.2389	.2536	.2679	.2818	.2953	.3084	.3212	.3336	.3457
85	.0334	.0599	.0839	.1063	.1274	.1474	.1665	.1849	.2025	.2195	.2359	.2518	.2671	.2820	.2965	.3105	.3241	.3374	.3503	.3629
90	.0353	.0633	.0887	.1122	.1344	.1554	.1754	.1946	.2131	.2308	.2479	.2644	.2804	.2959	.3109	.3254	.3395	.3533	.3666	.3795
95	.0373	.0667	.0934	.1180	.1413	.1633	.1842	.2043	.2235	.2419	.2597	.2769	.2935	.3095	.3250	.3400	.3546	.3687	.3824	.3958
100	.0392	.0701	.0980	.1239	.1481	.1711	.1929	.2138	.2337	.2529	.2714	.2891	.3063	.3228	.3388	.3543	.3693	.3838	.3979	.4116
105	.0411	.0735	.1027	.1296	.1549	.1788	.2015	.2232	.2439	.2637	.2828	.3011	.3188	.3359	.3524	.3683	.3837	.3986	.4130	.4270
110	.0430	.0769	.1073	.1354	.1617	.1865	.2100	.2324	.2539	.2744	.2941	.3130	.3312	.3487	.3656	.3819	.3977	.4130	.4277	.4420
115	.0449	.0802	.1119	.1411	.1684	.1941	.2184	.2416	.2637	.2849	.3051	.3246	.3433	.3613	.3786	.3953	.4114	.4270	.4420	.4566
120	.0468	.0835	.1164	.1467	.1750	.2016	.2268	.2507	.2735	.2952	.3161	.3360	.3562	.3736	.3913	.4084	.4248	.4407	.4560	.4708
125	.0487	.0869	.1210	.1523	.1816	.2091	.2350	.2596	.2831	.3054	.3268	.3473	.3669	.3857	.4038	.4212	.4379	.4541	.4696	.4846
130	.0506	.0902	.1255	.1579	.1881	.2164	.2432	.2685	.2926	.3155	.3374	.3583	.3783	.3976	.4160	.4337	.4507	.4671	.4829	.4981
135	.0525	.0936	.1300	.1635	.1946	.2238	.2512	.2772	.3019	.3254	.3478	.3692	.3896	.4092	.4280	.4460	.4633	.4799	.4959	.5113
140	.0544	.0968	.1345	.1690	.2010	.2310	.2592	.2859	.3111	.3352	.3580	.3798	.4007	.4206	.4397	.4579	.4755	.4923	.5085	.5240
145	.0563	.1000	.1389	.1745	.2074	.2382	.2671	.2944	.3203	.3448	.3681	.3903	.4115	.4318	.4511	.4697	.4874	.5045	.5208	.5365
150	.0582	.1033	.1434	.1799	.2137	.2453	.2749	.3028	.3292	.3543	.3780	.4006	.4222	.4427	.4624	.4811	.4991	.5163	.5328	.5486

Table 5.16: Precipitation Efficiency Factors - Swept Sine Vibration Screens (Continued)

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
155	.0601	.1066	.1478	.1853	.2200	.2523	.2827	.3112	.3381	.3636	.3878	.4108	.4326	.4535	.4734	.4924	.5105	.5279	.5445	.5604
160	.0620	.1098	.1522	.1907	.2262	.2593	.2903	.3194	.3469	.3728	.3974	.4207	.4429	.4640	.4842	.5034	.5217	.5392	.5559	.5719
165	.0638	.1130	.1565	.1960	.2324	.2662	.2979	.3275	.3555	.3819	.4069	.4305	.4530	.4744	.4947	.5141	.5326	.5502	.5670	.5831
170	.0657	.1163	.1609	.2013	.2385	.2731	.3053	.3356	.3640	.3908	.4162	.4402	.4629	.4845	.5051	.5246	.5432	.5610	.5779	.5941
175	.0676	.1195	.1652	.2066	.2446	.2799	.3128	.3435	.3724	.3997	.4254	.4496	.4727	.4945	.5152	.5349	.5536	.5715	.5885	.6047
180	.0694	.1227	.1695	.2118	.2507	.2866	.3201	.3514	.3807	.4083	.4344	.4590	.4822	.5042	.5251	.5450	.5638	.5817	.5988	.6150
185	.0713	.1258	.1737	.2170	.2566	.2933	.3273	.3591	.3889	.4169	.4433	.4681	.4916	.5138	.5348	.5548	.5737	.5917	.6088	.6251
190	.0731	.1290	.1780	.2222	.2626	.2999	.3345	.3668	.3970	.4253	.4520	.4771	.5008	.5232	.5444	.5644	.5834	.6015	.6186	.6349
195	.0750	.1322	.1822	.2273	.2685	.3064	.3416	.3744	.4050	.4337	.4606	.4860	.5098	.5324	.5537	.5739	.5929	.6110	.6282	.6445
200	.0768	.1353	.1864	.2324	.2743	.3129	.3486	.3818	.4128	.4419	.4691	.4947	.5187	.5414	.5628	.5831	.6022	.6203	.6375	.6538
205	.0787	.1385	.1906	.2374	.2801	.3193	.3556	.3892	.4206	.4499	.4774	.5032	.5274	.5503	.5718	.5921	.6113	.6294	.6466	.6628
210	.0805	.1416	.1948	.2425	.2858	.3257	.3624	.3965	.4283	.4579	.4856	.5116	.5360	.5590	.5806	.6009	.6201	.6383	.6554	.6716
215	.0823	.1447	.1989	.2475	.2915	.3320	.3692	.4037	.4358	.4657	.4937	.5199	.5444	.5675	.5891	.6096	.6288	.6469	.6641	.6802
220	.0842	.1478	.2030	.2524	.2972	.3382	.3759	.4109	.4433	.4735	.5016	.5280	.5527	.5758	.5976	.6180	.6372	.6554	.6725	.6886
225	.0860	.1509	.2071	.2573	.3028	.3444	.3826	.4179	.4506	.4811	.5095	.5360	.5608	.5840	.6058	.6263	.6455	.6636	.6807	.6966
230	.0878	.1540	.2112	.2622	.3084	.3505	.3892	.4249	.4579	.4886	.5172	.5438	.5687	.5920	.6139	.6343	.6536	.6717	.6887	.7047
235	.0897	.1570	.2153	.2671	.3139	.3566	.3957	.4317	.4651	.4960	.5248	.5515	.5765	.5999	.6218	.6423	.6615	.6795	.6965	.7124
240	.0915	.1601	.2193	.2719	.3194	.3626	.4021	.4385	.4722	.5033	.5322	.5591	.5842	.6076	.6295	.6500	.6692	.6872	.7041	.7199
245	.0933	.1632	.2233	.2767	.3248	.3685	.4085	.4452	.4791	.5105	.5396	.5666	.5917	.6162	.6371	.6576	.6767	.6947	.7115	.7273
250	.0951	.1662	.2273	.2815	.3302	.3744	.4148	.4519	.4860	.5176	.5468	.5739	.5991	.6226	.6445	.6650	.6841	.7020	.7187	.7344
255	.0969	.1692	.2313	.2862	.3355	.3803	.4210	.4584	.4928	.5246	.5539	.5811	.6064	.6299	.6518	.6722	.6913	.7091	.7258	.7414
260	.0987	.1722	.2353	.2909	.3408	.3860	.4272	.4649	.4995	.5314	.5609	.5882	.6135	.6371	.6589	.6793	.6983	.7161	.7326	.7481
265	.1005	.1752	.2392	.2956	.3461	.3918	.4333	.4713	.5061	.5382	.5678	.5952	.6205	.6441	.6659	.6863	.7052	.7228	.7393	.7547
270	.1023	.1782	.2431	.3002	.3513	.3975	.4394	.4776	.5127	.5449	.5746	.6020	.6274	.6509	.6728	.6930	.7119	.7295	.7459	.7611
275	.1041	.1812	.2470	.3048	.3565	.4031	.4453	.4839	.5191	.5515	.5813	.6088	.6342	.6577	.6795	.6997	.7185	.7359	.7522	.7674
280	.1059	.1842	.2509	.3094	.3616	.4087	.4512	.4900	.5255	.5580	.5879	.6154	.6408	.6643	.6860	.7062	.7249	.7423	.7584	.7735
285	.1077	.1871	.2547	.3140	.3667	.4142	.4571	.4961	.5318	.5644	.5943	.6219	.6473	.6708	.6925	.7125	.7312	.7484	.7645	.7794
290	.1095	.1901	.2586	.3185	.3718	.4196	.4629	.5021	.5379	.5707	.6007	.6283	.6537	.6771	.6987	.7186	.7373	.7544	.7704	.7852
295	.1112	.1930	.2624	.3230	.3768	.4251	.4686	.5081	.5441	.5769	.6070	.6346	.6600	.6833	.7049	.7248	.7433	.7603	.7761	.7908
300	.1130	.1960	.2662	.3275	.3818	.4304	.4743	.5140	.5501	.5830	.6131	.6408	.6661	.6895	.7110	.7308	.7491	.7661	.7817	.7963

Table 5.16: Precipitation Efficiency Factors - Swept Sine Vibration (Continued)

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
305	.1148	.1989	.2699	.3319	.3867	.4357	.4799	.5198	.5560	.5891	.6192	.6468	.6722	.6955	.7169	.7366	.7548	.7717	.7872	.8016
310	.1165	.2018	.2737	.3363	.3916	.4410	.4854	.5255	.5619	.5950	6252	.6528	.6781	.7013	.7227	.7423	.7604	.7771	.7925	.8068
315	.1183	.2047	.2774	.3407	.3965	.4462	.4909	.5312	.5677	.6009	.6311	.6587	.6839	.7071	.7283	.7479	.7659	.7824	.7977	.8118
320	.1201	.2076	.2812	.3450	.4013	.4514	.4963	.5368	.5734	.6066	.6369	.6645	.6897	.7127	.7339	.7533	.7712	.7876	.8028	.8168
325	.1218	.2104	.2848	.3493	.4061	.4565	.5017	.5423	.5791	.6123	.6426	.6701	.6953	.7183	.7394	.7587	.7764	.7927	.8077	.8216
330	.1236	.2133	.2885	.3536	.4108	.4616	.5070	.5478	.5846	.6179	.6482	.6757	.7008	.7237	.7447	.7639	.7815	.7977	.8126	.8262
335	.1253	.2162	.2922	.3579	.4155	.4686	.5123	.5532	.5901	.6235	.6537	.6812	.7062	.7291	.7499	7690	.7865	.8025	.8172	.8308
340	.1271	.2190	.2958	.3621	.4202	.4716	.5175	.5586	.5955	.6289	.6592	.6866	.7116	.7343	.7550	.7740	.7914	.8072	.8218	.8352
345	.1288	.2218	.2995	.3663	.4248	.4765	.5226	.5638	.6009	.6343	.6645	.6919	.7168	.7394	.7601	.7789	.7961	.8119	.8263	.8395
350	.1306	.2247	.3031	.3705	.4294	.4814	.5277	.5690	.6062	.6396	.6698	.6971	.7219	.7445	.7650	.7837	.8008	.8164	.8306	.8437
355	.1323	.2275	.3066	.3746	.4340	.4863	.5327	.5742	.6114	.6448	.6750	.7022	.7269	.7494	.7698	.7884	.8053	.8208	.8349	.8478
360	.1340	.2303	.3102	.3787	.4385	.4911	.5377	.5793	.6165	.6499	.6801	.7073	.7319	.7542	.7745	.7929	.8097	.8250	.8390	.8518
365	.1358	.2331	.3138	.3828	.4430	.4968	.5426	.5843	.6216	.6550	.6851	.7122	.7368	.7590	.7791	.7974	.8141	.8292	8431	.8557
370	.1375	.2358	.3173	.3869	.4474	.5005	.5475	.5893	.6266	.6600	.6900	.7171	.7415	.7636	.7836	.8018	.8183	.8333	.8470	.8594
375	.1392	.2386	.3208	.3909	.4518	.5052	.5523	.5942	.6315	.6649	.6949	.7219	.7462	.7682	.7881	.8061	.8224	.8373	.8508	.8631
380	.1409	.2414	.3243	.3950	.4562	.5098	.5571	.5990	.6364	.6698	.6997	.7266	.7508	.7727	.7924	.8103	.8265	.8412	.8546	.8667
385	.1426	.2441	.3278	.3990	.4605	.5144	.5618	.6038	.6412	.6746	.7044	.7312	.7553	.7770	.7967	.8144	.8304	.8450	.8582	.8702
390	.1443	.2469	.3312	.4029	.4648	.5189	.5665	.6086	.6459	.6793	.7091	.7358	.7598	7813	.8008	.8184	.8343	.8487	.8617	.8736
395	.1461	.2496	.3347	.4068	.4691	.5234	.5711	.6132	.6506	.6839	.7136	.7402	.7641	.7856	.8049	.8223	.8381	.8523	8652	.8769
400	.1478	.2523	.3381	.4108	.4734	.5279	.5757	.6179	.6552	.6885	.7181	.7446	.7684	.7897	.8089	.8262	.8418	.8558	.8686	.8801
405	.1495	.2550	.3415	.4146	.4776	.5323	.5802	.6224	.6598	.6930	.7225	.7489	.7726	.7938	.8128	.8299	.8454	.8593	.8719	.8833
410	.1512	.2578	.3449	.4185	.4817	.5366	.5847	.6270	.6643	.6974	.7269	.7532	.7767	.7977	.8166	.8336	.8489	.8627	.8751	.8863
415	.1529	.2604	.3483	.4223	.4859	.5410	.5891	.6314	.6687	.7018	.7312	.7574	.7807	.8016	.8204	.8372	.8523	.8659	.8782	.8893
420	.1545	.2631	.3516	.4261	.4900	.5453	.5935	.6358	.6731	.7061	.7354	.7615	.7847	.8055	.8241	.8407	.8557	.8692	.8813	.8922
425	.1562	.2658	.3549	.4299	.4940	.5495	.5978	.6402	.6774	.7104	.7396	.7655	.7886	.8092	.8277	.8442	.8590	.8723	.8842	.8950
430	.1579	.2685	.3583	.4337	.4981	.5537	.6021	.6445	.6817	.7146	.7437	.7695	.7924	.8129	.8312	.8475	.8622	.8753	.8871	.8978
435	.1596	.2711	.3616	.4374	.5021	.5579	.6064	.6487	.6859	.7187	.7477	.7734	.7962	.8165	.8347	.8506	.8653	.8783	.8900	.9004
440	.1613	.2738	.3648	.4411	.5061	.5620	.6105	.6529	.6901	.7228	.7516	.7772	.7999	.8201	.8380	.8541	.8684	.8812	.8927	.9030
445	.1629	.2764	.3681	.4448	.5100	.5661	.6147	.6571	.6942	.7268	.7555	.7810	.8035	.8235	.8414	.8572	.8714	.8841	.8954	.9056
450	.1646	.2790	.3714	.4485	.5139	.5701	.6188	.6612	.6982	.7307	.7594	.7847	.8071	.8269	.8446	.8603	.8743	.8868	.8980	.9080

Table 5.16: Precipitation Efficiency Factors - Swept Sine Vibration Screens (Continued)

	ACCELERATION LEVEL (G - RMS)																			
DURATION (MINUTES)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
455	.1663	.2816	.3746	.4521	.5178	.5742	.6229	.6652	.7022	.7346	.7632	.7883	.8106	.8303	.8478	.8633	.8772	.8896	.9006	.9104
460	.1680	.2842	.3778	.4557	.5217	.5781	.6269	.6692	.7061	.7385	.7669	.7919	.8140	.8336	.8509	.8663	.8800	.8922	.9031	.9128
465	.1696	.2868	.3810	.4593	.5256	.5821	.6309	.6732	.7100	.7423	.7705	.7954	.8174	.8368	.8540	.8692	.8827	.8948	.9055	.9151
470	.1713	.2894	.3842	.4628	.5293	.5860	.6348	.6771	.7139	.7460	.7741	.7989	.8207	.8399	.8569	.8720	.8854	.8973	.9079	.9173
475	.1729	.2920	.3874	.4664	.5330	.5898	.6387	.6809	.7176	.7497	.7777	.8023	.8239	.8430	.8599	.8748	.8880	.8997	.9102	.9195
480	.1746	.2946	.3905	.4699	.5367	.5937	.6425	.6848	.7214	.7533	.7812	.8056	.8271	.8460	.8627	.8775	.8906	.9021	.9124	.9216
485	.1762	.2971	.3937	.4734	.5404	.5976	.6464	.6885	.7251	.7569	.7846	.8089	.8303	.8490	.8656	.8801	.8931	.9045	.9146	.9236
490	.1779	.2997	.3968	.4769	.5441	.6012	.6501	.6922	.7287	.7604	.7880	.8122	.8333	.8519	.8683	.8827	.8955	.9068	.9168	.9256
495	.1795	.3022	.3999	.4803	.5478	.6049	.6539	.6959	.7323	.7638	.7913	.8153	.8363	.8548	.8710	.8853	.8979	.9090	.9188	.9276
500	.1812	.3048	.4030	.4837	.5514	.6086	.6575	.6996	.7358	.7673	.7946	.8185	.8393	.8576	.8736	.8878	.9002	.9112	.9209	.9295
505	.1828	.3073	.4060	.4871	.5549	.6123	.6612	.7031	.7393	.7706	.7978	.8215	.8422	.8603	.8762	.8902	.9025	.9133	.9229	.9313
510	.1844	.3098	.4091	.4905	.5585	.6159	.6648	.7067	.7428	.7740	.8010	.8245	.8451	.8630	.8788	.8926	.9047	.9154	.9248	.9331
515	.1860	.3123	.4121	.4939	.5620	.6195	.6684	.7102	.7462	.7772	.8041	.8275	.8479	.8657	.8812	.8949	.9069	.9174	.9267	.9349
520	.1877	.3148	.4152	.4972	.5655	.6231	.6719	.7137	.7495	.7804	.8072	.8304	.8506	.8683	.8837	.8972	.9090	.9194	.9285	.9366
525	.1893	.3173	.4182	.5005	.5690	.6266	.6754	.7171	.7528	.7836	.8102	.8333	.8534	.8708	.8861	.8994	.9111	.9213	.9303	.9382
530	.1909	.3198	.4212	.5038	.5724	.6301	.6789	.7205	.7561	.7868	.8132	.8361	.8560	.8733	.8884	.9016	.9131	.9232	.9320	.9398
535	.1925	.3222	.4241	.5071	.5758	.6335	.6823	.7238	.7593	.7898	.8162	.8389	.8586	.8758	.8907	.9037	.9151	.9250	.9338	.9414
540	.1941	.3247	.4271	.5103	.5792	.6369	.6857	.7271	.7625	.7929	.8190	.8416	.8612	.8782	.8929	.9058	.9170	.9268	.9354	.9429
545	.1957	.3271	.4301	.5136	.5826	.6403	.6890	.7304	.7657	.7959	.8219	.8443	.8637	.8805	.8951	.9078	.9189	.9286	.9370	.9444
550	.1974	.3296	.4330	.5168	.5859	.6437	.6923	.7336	.7688	.7988	.8247	.8469	.8662	.8828	.8973	.9098	.9207	.9303	.9386	.9459
555	.1990	.3320	.4359	.5200	.5892	.6470	.6956	.7368	.7718	.8017	.8274	.8495	.8686	.8851	.8994	.9118	.9225	.9319	.9401	.9473
560	.2006	.3344	.4388	.5231	.5925	.6503	.6989	.7399	.7748	.8046	.8301	.8521	.8710	.8873	.9014	.9137	.9243	.9336	.9416	.9487
565	.2022	.3369	.4417	.5263	.5958	.6536	.7021	.7430	.7778	.8074	.8328	.8546	.8733	.8895	.9034	.9155	.9260	.9352	.9431	.9500
570	.2037	.3393	.4446	.5294	.5990	.6568	.7053	.7461	.7807	.8102	.8354	.8570	.8756	.8916	.9054	.9174	.9277	.9367	.9445	.9513
575	.2053	.3417	.4474	.5325	.6022	.6600	.7084	.7491	.7836	.8130	.8380	.8595	.8779	.8937	.9073	.9192	.9294	.9382	.9459	.9526
580	.2069	.3440	.4503	.5356	.6054	.6632	.7115	.7521	.7865	.8157	.8406	.8618	.8801	.8957	.9092	.9209	.9310	.9397	.9473	.9538
585	.2085	.3464	.4531	.5386	.6085	.6663	.7146	.7551	.7893	.8184	.8431	.8642	.8822	.8978	.9111	.9226	.9325	.9411	.9486	.9551
590	.2101	.3488	.4559	.5417	.6116	.6694	.7176	.7580	.7921	.8210	.8455	.8665	.8844	.8997	.9129	.9243	.9341	.9426	.9499	.9562
595	.2117	.3512	.4587	.5447	.6147	.6725	.7206	.7609	.7949	.8236	.8480	.8687	.8865	.9017	.9147	.9259	.9356	.9439	.9511	.9574
600	.2132	.3535	.4615	.5477	.6178	.6756	.7236	.7638	.7976	.8261	.8503	.8709	.8885	.9036	.9165	.9275	.9371	.9453	.9524	.9585

Table 5.17: Precipitation Efficiency Factors - Constant Temperature Screens

TIME IN HOURS	TEMPERATURE DELTA (ΔT) - °C								
	0	10	20	30	40	50	60	70	80
10	.0124	.0677	.0992	.1240	.1452	.1639	.1809	.1964	.2108
20	.0247	.1308	.1885	.2326	.2693	.3010	.3290	.3542	.3772
30	.0368	.1896	.2689	.3278	.3754	.4156	.4504	.4810	.5084
40	.0488	.2445	.3414	.4112	.4661	.5114	.5498	.5830	.6121
50	.0606	.2956	.4067	.4842	.5436	.5915	.6312	.6649	.6938
60	.0723	.3433	.4655	.5481	.6099	.6584	.6979	.7307	.7584
70	.0839	.3877	.5185	.6042	.6665	.7144	.7525	.7836	.8093
80	.0953	.4292	.5663	.6533	.7149	.7612	.7973	.8261	.8495
90	.1065	.4678	.6093	.6963	.7563	.8004	.8339	.8602	.8812
100	.1176	.5038	.6480	.7339	.7917	.8331	.8640	.8877	.9063
110	.1286	.5374	.6829	.7669	.8219	.8605	.8886	.9097	.9260
120	.1394	.5687	.7144	.7958	.8478	.8833	.9087	.9275	.9416
130	.1501	.5979	.7427	.8211	.8699	.9025	.9252	.9417	.9539
140	.1607	.6251	.7682	.8433	.8888	.9184	.9388	.9532	.9636
150	.1711	.6505	.7912	.8628	.9049	.9318	.9498	.9624	.9713
160	.1814	.6742	.8119	.8798	.9187	.9430	.9589	.9697	.9774
170	.1916	.6962	.8305	.8947	.9305	.9523	.9663	.9757	.9821
180	.2017	.7168	.8473	.9077	.9406	.9602	.9724	.9805	.9859
190	.2116	.7360	.8625	.9192	.9492	.9667	.9774	.9843	.9889
200	.2214	.7538	.8761	.9292	.9566	.9721	.9815	.9874	.9912
210	.2311	.7705	.8884	.9380	.9629	.9767	.9848	.9899	.9931
220	.2406	.7860	.8995	.9457	.9683	.9805	.9876	.9919	.9945
230	.2501	.8005	.9094	.9524	.9729	.9837	.9898	.9935	.9957
240	.2594	.8140	.9184	.9583	.9768	.9864	.9917	.9947	.9966
250	.2686	.8266	.9265	.9635	.9802	.9886	.9932	.9958	.9973
260	.2777	.8383	.9338	.9680	.9831	.9905	.9944	.9966	.9979
270	.2867	.8493	.9403	.9720	.9855	.9920	.9954	.9973	.9983
280	.2956	.8595	.9463	.9755	.9876	.9933	.9962	.9978	.9987
290	.3043	.8690	.9516	.9785	.9894	.9944	.9969	.9982	.9990
300	.3130	.8779	.9564	.9812	.9910	.9954	.9975	.9986	.9992

Table 5.17: Precipitation Efficiency Factors - Constant Temperature Screens (Continued)

TIME IN HOURS	TEMPERATURE DELTA (ΔT) - °C								
	0	10	20	30	40	50	60	70	80
310	.3215	.8861	.9607	.9835	.9923	.9961	.9979	.9989	.9994
320	.3299	.8938	.9646	.9855	.9934	.9968	.9983	.9991	.9995
330	.3383	.9010	.9681	.9873	.9944	.9973	.9986	.9993	.9996
340	.3465	.9077	.9713	.9889	.9952	.9977	.9989	.9994	.9997
350	.3546	.9140	.9741	.9903	.9959	.9981	.9991	.9995	.9997
360	.3627	.9198	.9767	.9915	.9965	.9984	.9992	.9996	.9998
370	.3706	.9252	.9790	.9925	.9970	.9987	.9994	.9997	.9998
380	.3784	.9303	.9811	.9935	.9974	.9989	.9995	.9998	.9999
390	.3861	.9350	.9830	.9943	.9978	.9991	.9996	.9998	.9999
400	.3938	.9394	.9847	.9950	.9981	.9992	.9997	.9998	.9999
410	.4013	.9435	.9862	.9956	.9984	.9994	.9997	.9999	.9999
420	.4088	.9473	.9875	.9962	.9986	.9995	.9998	.9999	1.0000
430	.4161	.9509	.9888	.9966	.9988	.9995	.9998	.9999	1.0000
440	.4234	.9542	.9899	.9970	.9990	.9996	.9998	.9999	1.0000
450	.4305	.9573	.9909	.9974	.9991	.9997	.9999	.9999	1.0000
460	.4376	.9602	.9918	.9977	.9993	.9997	.9999	1.0000	1.0000
470	.4446	.9629	.9926	.9980	.9994	.9998	.9999	1.0000	1.0000
480	.4515	.9654	.9933	.9983	.9995	.9998	.9999	1.0000	1.0000
490	.4583	.9677	.9940	.9985	.9995	.9998	.9999	1.0000	1.0000
500	.4651	.9699	.9946	.9987	.9996	.9999	1.0000	1.0000	1.0000
510	.4717	.9720	.9951	.9988	.9997	.9999	1.0000	1.0000	1.0000
520	.4783	.9739	.9956	.9990	.9997	.9999	1.0000	1.0000	1.0000
530	.4848	.9756	.9961	.9991	.9998	.9999	1.0000	1.0000	1.0000
540	.4912	.9773	.9964	.9992	.9998	.9999	1.0000	1.0000	1.0000
550	.4975	.9788	.9968	.9993	.9998	.9999	1.0000	1.0000	1.0000
560	.5038	.9803	.9971	.9994	.9998	1.0000	1.0000	1.0000	1.0000
570	.5099	.9816	.9974	.9995	.9999	1.0000	1.0000	1.0000	1.0000
580	.5160	.9828	.9977	.9995	.9999	1.0000	1.0000	1.0000	1.0000
590	.5220	.9840	.9979	.9996	.9999	1.0000	1.0000	1.0000	1.0000
600	.5280	.9851	.9981	.9996	.9999	1.0000	1.0000	1.0000	1.0000

5.5 Procedure D - Refining Estimates of Defect Density and Screening Strength

5.5.1 **Objective.** To refine the estimates of ESS modeling parameters (D_{IN}, SS, $D_{REMAINING}$, etc.) using actual factory and field data.

5.5.2 **Methodology.** The most important parameter for ESS is the defects remaining at the time of shipment since this determines the field reliability. Other significant parameters are the initial defect density, and the screening strength of various screens. The difficulty, however, is that none of these parameters are directly observable by the producer. Only the defects removed through factory ESS can be measured. This procedure provides the means for determining these other critical parameters from the factory data.

5.5.3 Procedure Steps.

Step 1. Collect the necessary factory (test and failure) data from a FRACAS system. When assembling this data it is imperative to distinguish between errors and defects. Errors are preventable and usually detectable without environmental stress. The primary concern of this procedure is the elimination of latent defects. The minimum data requirements for the FRACAS system are:

ESS Test Equipment
Stress Duration - times at start of test, completion of test, and time of failure
Test Type
Number of units tested - number that pass/fail
Assembly - Sub Assembly - part failed
Failure Cause
Details of the ESS process
History of environment leading to failure

Collect the fallout data for each type of environment (i.e., temperature cycling, random vibration etc.) separately and prepare graphs with the cumulative defects, normalized as defects per system as the ordinate, and the stress duration as the abscissa.

Step 2. Determination Of D_{IN}, PE, SS, and $D_{REMAINING}$. The method of determining D_{IN}, PE, SS, and $D_{REMAINING}$ is either through use of a computerized or hand curve fitting technique depending on available resources. Step 2a describes the computerized approach and step 2b the hand approach.

Step 2a. Computerized Curve Fitting Approach. This method is preferred as it will yield more accurate results. An automated least squares error multiple regression, maximum likelihood or other estimation tool is required. Several canned computerized methods are available.

Curve fit the factory fallout data (determined in step 1) and field data to the following expression:

$$D_{REMOVED} = DE\,[D_{PAT} + D_{LAT}\,[1-\exp(-kt)] + CFR^{*}t]$$

Set up the curve fitting technique to extract values of D_{PAT}, D_{LAT}, k, and CFR. Figure 5.9 illustrates a sample curve fitting analysis. The derivation of the expression for $D_{REMOVED}$ is discussed in Appendix A and Rome Laboratory technical report RL-TR-91-300 and has been found to be adequately representative of the real world.

Proceed to step 3 to determine values of D_{IN}, PE, SS, and $D_{REMAINING}$.

Step 2b. Hand Curve Fitting Approach. In general, the user will see an exponentially distributed plot similar to that shown in figure 5.10.

From the plot, the user can derive rough approximations of D_{PAT}, D_{LAT}, k, and CFR as follows. It is first necessary to divide the curve into two areas as illustrated in figure 5.11.

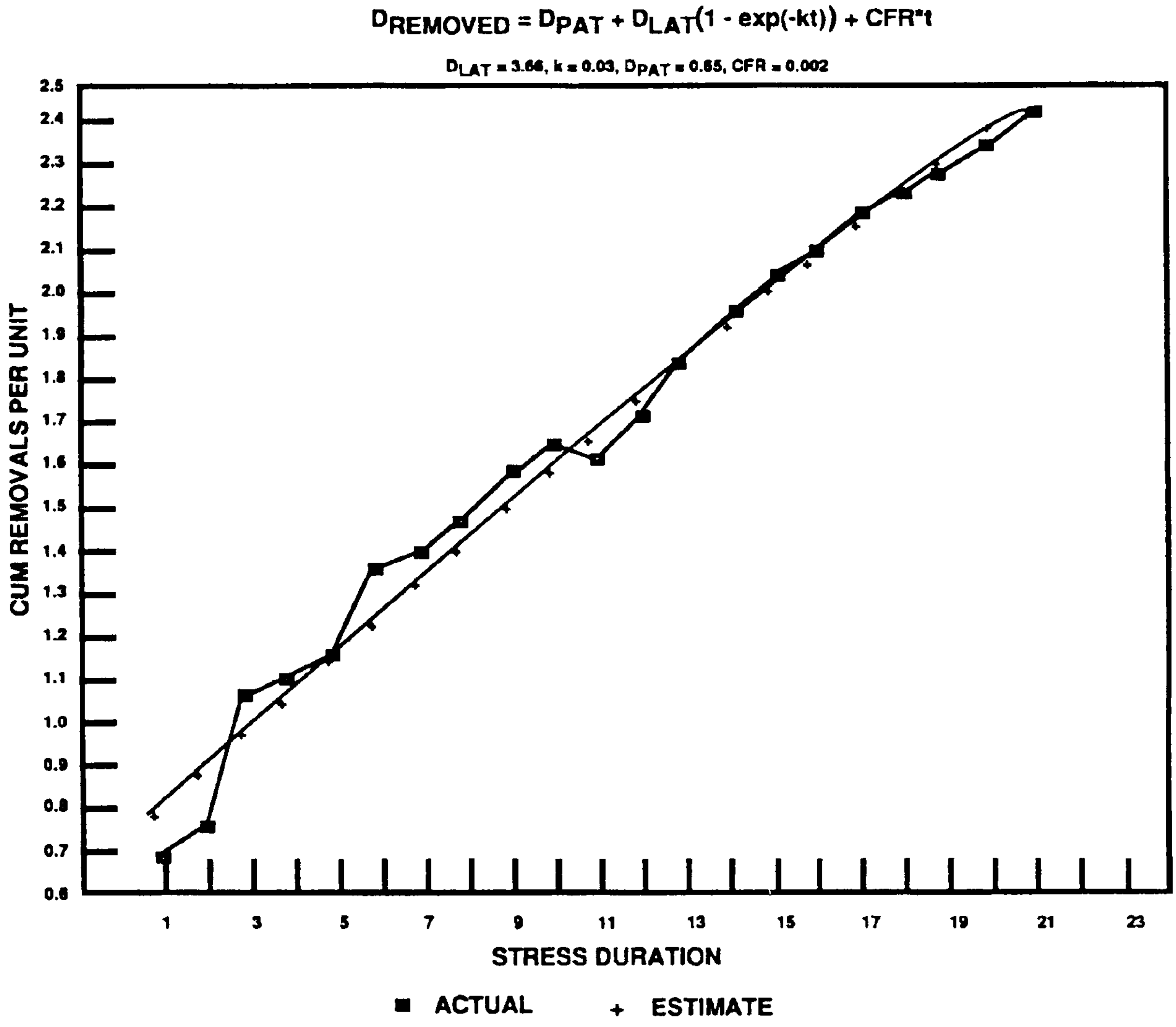


Figure 5.9: Sample Curve Fitting Analysis

Estimation of D_{PAT}

- D_{PAT} is estimated from the "y" intercept extrapolated from the plot.

Estimation of CFR

- CFR is approximately equal to the slope of the straight line region of the plot.

Estimation of D_{LAT} and k

Background: The curved region of the plot can be represented as $D_{REMOVED} = D_{LAT}[1 - \exp(-kt)]$. The first derivative of this expression yields $\frac{d(D_{LAT})}{dt} = kD_{LAT}e^{-kt}$. To estimate D_{LAT} and k it is necessary to plot values of the slope between points on the original plot (that plotted in step 1 above). The values are to be plotted on semilog paper. Taking the natural log of the above expression yields ln(kD_{LAT}) - kt. This can be approximated as a straight line on semilog paper where k is approximately equal to the negative value of the slope and kD_{LAT} is approximately equal to the "y" intercept. The following steps walk through the method to estimate D_{LAT}.

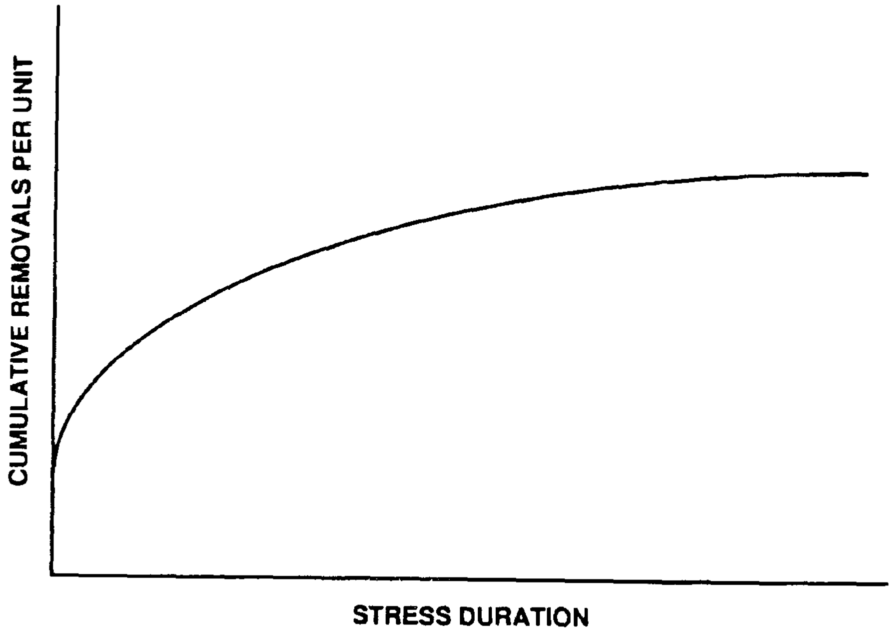


Figure 5.10: Expected Form of Hand Plotted Defect Distribution

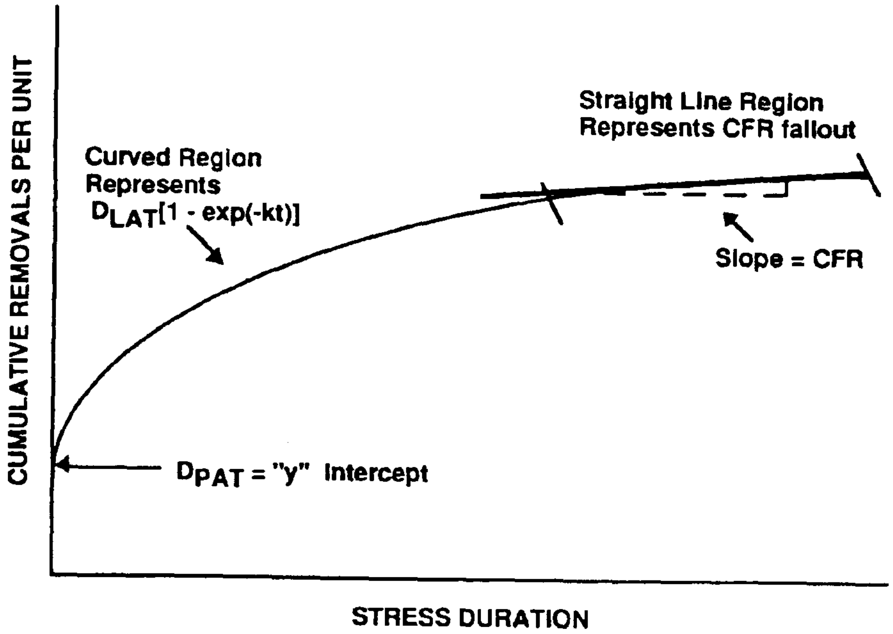


Figure 5.11: Breakdown of Defect Distribution Curve

- On semilog paper plot values of the slope of each line segment formed by consecutive points of the original plot as the ordinate and time as the abscissa. See figure 5.12 below.

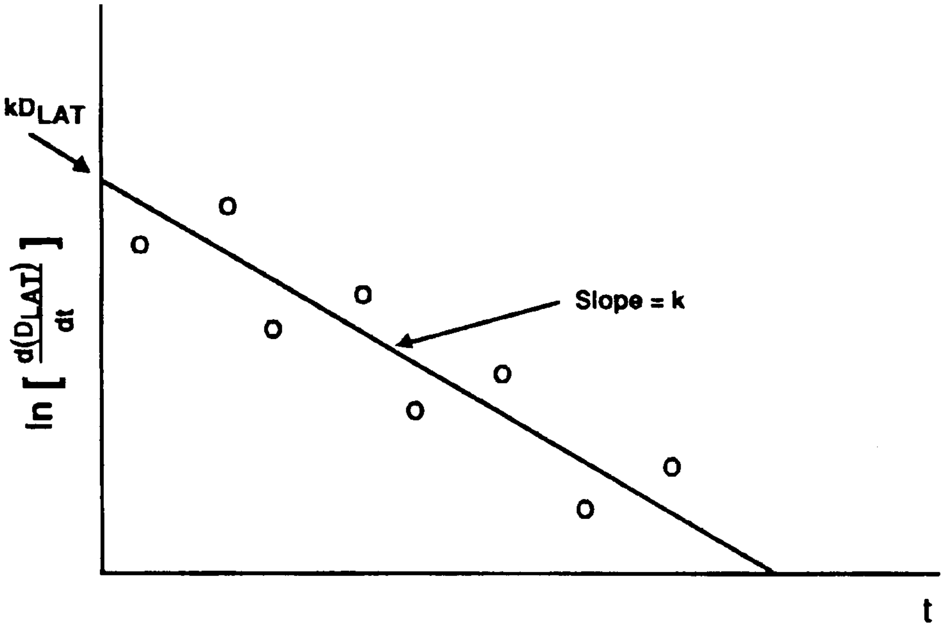


Figure 5.12: $\frac{d(D_{LAT})}{dt}$ vs. Time On Semilog Paper

- Determine the " best fit" straight line through the plotted points.

- From this line calculate the slope. The estimated stress constant k is equal to the value of (- slope).

- The "y" - intercept is equal to kD_{LAT}. Determine D_{LAT} as $D_{LAT} = \frac{kD_{LAT}}{k}$

Proceed to step 3 to determine values of D_{IN}, PE, SS, and $D_{REMAINING}$.

Step 3. Determination of D_{IN}, PE, SS, $D_{REMAINING}$, and SAF

Determination of D_{IN}. D_{IN} is simply calculated as $D_{IN} = D_{PAT} + D_{LAT}$ where D_{PAT} and D_{LAT} are those values found in step 2a or 2b as appropriate.

Determination of PE and SS. Recalling Procedure C, screening strength is the product of precipitation efficiency (PE) and detection efficiency (DE). Curve fitting the factory fallout data yields the "k" value (stress constant). PE is calculated as $PE = 1 - e^{-kt}$. If field data is available, the detection efficiency of factory ESS can be determined as follows.

$$DE(factory) = \frac{D_{PAT}(field)}{Factory\ Fallout}$$

where D_{PAT} is determined in 2a or 2b above.

SS is then calculated as SS = PE x DE

Note: If field data isn't available assume DE = 1.

Determination of $D_{REMAINING}$. $D_{REMAINING}$ is simply calculated as $D_{REMAINING} = D_{IN} - D_{REMOVED}$ where D_{IN} is found in the first part of step 3 and $D_{REMOVED}$ is determined through fallout observation.

Determination of Stress Adjustment Factor (SAF). If field data is available the SAF can be determined as:

$$SAF = \frac{D_{LAT}(\text{field})}{[D_{LAT}(\text{factory}) * (1 - SS(\text{factory}))]}$$

Step 4. Comparison of Actual vs. Planned Defect Density (D_{IN}) and Screening Strength (SS).

The observed fallout values of D_{IN} and SS can be above, below or equal to planning estimates. The worst case situation, in terms of effect on remaining defect density goals, is where D_{IN} is higher than the planning estimate and SS is lower. D_{IN} is reduced only through corrective actions which reduce further incoming defect density and thereby improves process capability. SS is increased by changing the screen type, stress levels or duration of the screen and by increasing the thoroughness of tests which are performed in conjunction with the screen. Table 5.18 illustrates the various possible conditions that can exist when the "true" values of D_{IN} and SS are compared against planning estimates. The conditions are ranked according to severity and grouped into four categories dependent upon whether outgoing defect density or costs are effected. The corrective actions required for each category are also shown in the table. Note that regardless of the outcome of the comparisons, corrective actions should always be taken to reduce D_{IN} when opportunities to do so are presented.

Table 5.18: Comparison of Actual vs. Planned Defect Density (D_{IN}) and Screening Strength (SS) Values

CONDITION		COMPARISON ACTUAL VS PLANNED D_{IN}	 SS	EFFECT ON REMAINING DEFECT DENSITY GOAL $D_{REMAINING}$	 FUTURE SCREENING COSTS	ACTIONS REQUIRED D_{IN} REDUCE D_{IN} BY CORRECTIVE ACTIONS	 SS CHANGES TO SCREEN/TEST
I	A	HI	LO	HIGHER THAN EXPECTED	INCREASE	ESSENTIAL	INCREASE SCREENING STRENGTH
	B	HI	OK				
	C	OK	LO				
II	D	HI	HI	IF HIGHER UNCERTAIN			
	E	LO	LO	IF LOWER			
III	F	OK	HI	LOWER THAN EXPECTED	REDUCE	BY OPPORTUNITY*	REDUCE SCREENING STRENGTH
	G	LO	OK				
	H	LO	HI				
IV	I	OK	OK	LIKELY TO BE ACHIEVED	REDUCE	BY OPPORTUNITY	NO CHANGE OR EVENTUALLY REDUCE

* Corrective actions should always be taken when the opportunity presents itself and the costs to take actions are reasonable

5.6 Procedure E - Monitor and Control

5.6.1 **Objective.** To implement a program to monitor and control the ESS program (consistent with TQM philosophy) thereby ensuring that the program remains cost effective under the evolving conditions.

5.6.2 **Methodology.** The parameters of interest for monitor and control (D_{IN}, SS, $D_{REMAINING}$, etc.) are determined in Procedure D. Modified SPC and PARETO charts are prepared to monitor these parameters against the requirements established in Procedure A.

5.6.3 Procedure Steps.

Step 1. Management monitor and control is accomplished by preparing SPC charts for the important parameters determined in Procedure D. Since the objective of ESS is continuous improvement in the elimination of defects and their causes, a homogeneity test is not adequate for D_{IN} and $D_{REMAINING}$ since they should be decreasing with time and product maturity. The SPC charts must also reflect the requirements (which are directly related to field reliability by $D_{REMAINING}$), the current level of performance, and the statistically expected variation due to limited sample size. With conventional SPC charts the parameter of interest remains relatively constant, so that the process average (μ) variation can be determined by taking the mean over many samples. For ESS however, the parameter of interest (μ) is expected to be improving with time making it necessary to use regression analysis. A second order polynomial regression analysis is usually adequate. The user could draw a smooth curve through the data with a French curve (or other means by hand) if a second order polynomial regression isn't feasible. What is important, is to determine the process capability and to extrapolate values of defect density for forward planning. Out of control conditions should be examined to compare the requirements with any variations. The amount of money required to understand and resolve an out of control condition should be determined along with the comparison. A slight variation may or may not be a problem depending on relative mission criticality/safety.

Figure 5.13 illustrates a modified SPC chart for monitoring the total incoming defects D_{IN}. It displays the TQM goals (inherently established as part of Procedure A) and compares actual results to these requirements. The expected statistical variation due to the limited sample size is calculated using a Poisson distribution and has a standard deviation given by $\sigma = \frac{\sqrt{\mu}}{n}$ where n is the sample size and μ is determined from the regression analysis.

Step 2. As a supplement to the SPC charts created in step 1 it is sometimes useful to generate a PARETO chart to display a breakdown of failure causes. The PARETO typically examines the frequency of various causes of non-conformities and indicates defect frequency and/or frequency percentage. The PARETO identifies the most frequent cause but not necessarily the most important cause and can over look what is expected based upon other considerations, for example complexity.

To overcome this, a modified PARETO is recommended that charts not only actual results, but compares them with the expected results based on complexity and statistical significance. When reviewing the PARETO diagram, situations where defects are either greater or less than expected require more in depth analysis. Since a design fault is often specific to a particular assembly, the PARETO chart can help identify potential design flaws by identifying assemblies with defect densities above expected levels. Conversely, assemblies with defect densities significantly lower than expected levels may indicate low screening stresses or low detection efficiency. If the SPC chart for a particular assembly continually trends above or below expected levels and detailed failure analyses do not reveal abnormal causes, then the cause may be to do with packaging density etc. If so, the expected goals and requirements for the particular assembly can be adjusted by a suitable correction factor and Procedure A repeated. Figure 5.14 illustrates a typical application of a PARETO chart. To allow for statistical variations due to sample size, the expected values are indicated as ±3 sigma bars (assuming a Poisson distribution as for the SPC charts). This makes it possible to identify not only assemblies with high and low defect densities but also those assemblies where the defect density is significantly different than expected. The PARETO is recommended because it not only charts actual results, but compares them with expected results based on complexity and statistical significance.

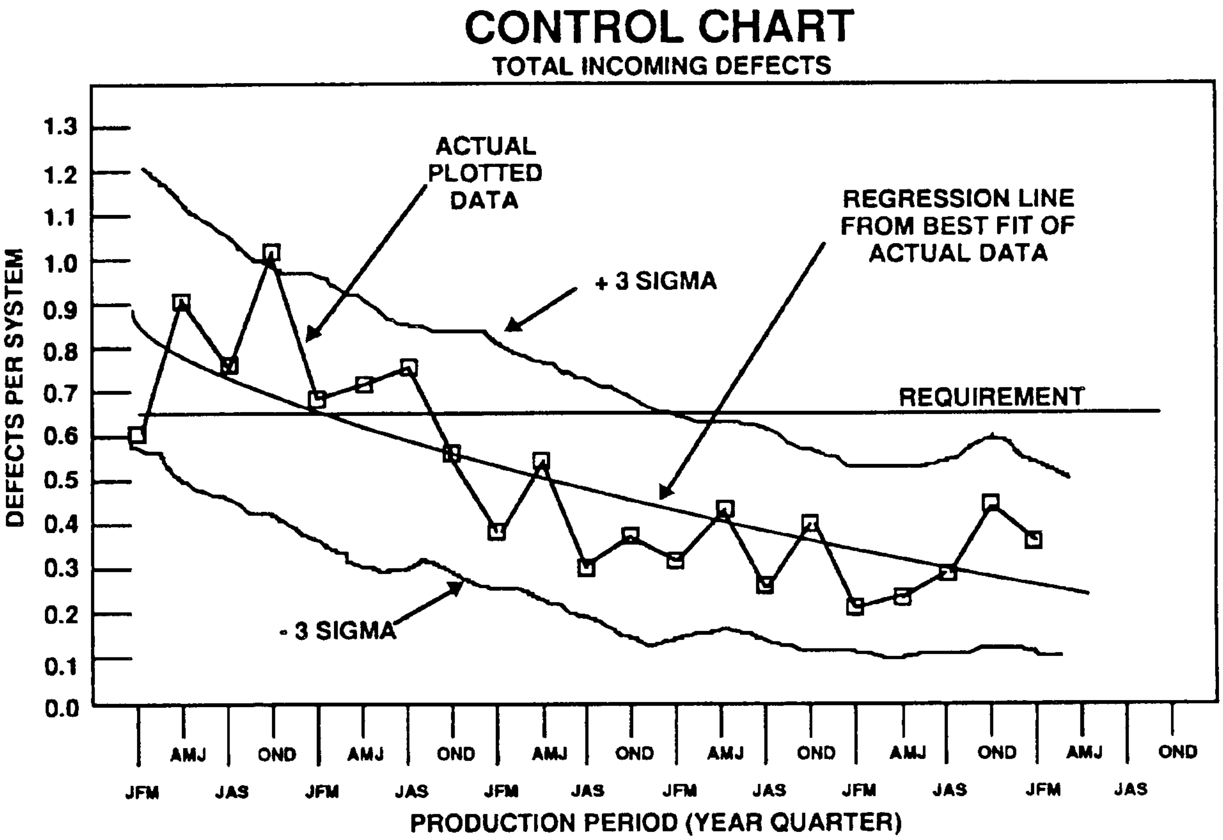


Figure 5-13: Sample SPC Chart

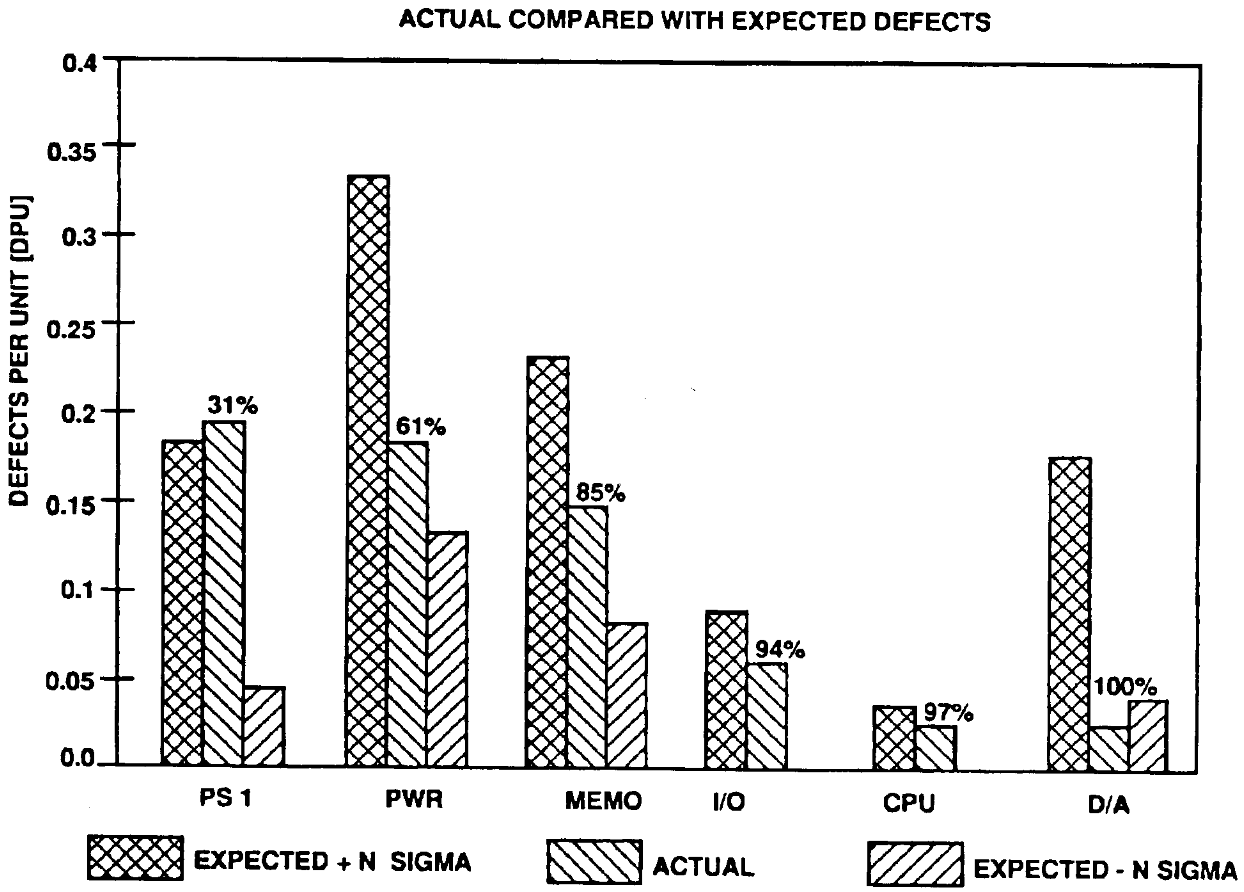


Figure 5-14: Sample PARETO Chart

5.7 Procedure F - Product Reliability Verification Test (PRVT)

5.7.1 Objective. To retain a minimum ESS so that field reliability can be projected and out of control conditions identified.

5.7.2 Methodology. The Monitor and Control Procedures of Procedure E determine whether or not outgoing reliability requirements are being met by comparing actual factory results with the goals (established in the design stage of Procedure A) via SPC and PARETO charts. Since these procedures ensure reliability is achieved, any further testing would be redundant. Recall that the ESS program operates in a feedback loop. The intent is to precipitate defects (in the factory) that would have occurred in the field and thus identify their causes so that corrective actions can be taken to prevent their recurring. This should continually reduce defect density thereby allowing for a reduction in ESS. However, the extension of this process is to completely eliminate ESS - thereby creating a situation in which there is no mechanism to indicate when the process is not in control and reliability is not being achieved. PRVT is defined as that portion of ESS retained for the purpose of providing such a mechanism and is inherently part of the ESS program (and subject to the Monitor and Control Procedure of Procedure D).

Any assessment of reliability must be made on the basis of the performance of the collective population in the field and the percentage of systems that are defective in a specified operating period (the assessment of factory performance must be made on the same basis). It is measured by implementing a monitor and control program based on normalized parameters (defects/system, defects/unit, etc.). The PRVT segment is to be monitored in this way. However, first pass yield (where first pass yield is defined as the number of systems completing the PRVT segment with no failures divided by the total number of systems first time submitted) is also applicable. Provided the defects are Poisson distributed, first pass yield and defects/system requirements are related by Yield = exp (-Defects).

If the SPC requirements (see Procedure E paragraph 5.6) and the PRVT requirements of first pass yield are not achieved, the outgoing system defect density is too high and corrective action must be taken that addresses the general population. If defect causes can not be immediately removed to attain an "in control" situation, ESS must be increased for all production (subject to the damage restrictions outlined in Procedure A) until "control" is re-established.

5.7.3 Procedure Steps.

Step 1. Using the mathematical derivations relating first pass yield to field reliability (MTBF) detailed in Appendix B, determine if the first pass yield is worse than required. If the first pass yield and the monitor and control technique of Procedure E indicates that the necessary field reliability is not being achieved, add ESS according to the methods outlined in Procedure A.

Step 2. As the ESS program evolves and ESS is reduced, ensure that as a minimum, one RV and two TC cycles are retained for the PRVT segment to help identify out of control conditions that would otherwise be missed.

APPENDIX A

Stress Screening Mathematical Model

10. **General.** The fundamental objective of a stress screening program is to reduce the number of latent defects in a production lot of equipment to an acceptable level by use of cost effective screening regimens. As basic principles, one would like to be able to use strong screens and efficient tests, within prescribed cost constraints, which have a high probability of precipitating and detecting defects and thus achieving reliability objectives. To transform these principles into quantitative procedures, it is necessary to define various measures and their relationships to the screening process. This Appendix defines a mathematical model that predicts/establishes relationships between quantities such as defect density, precipitation efficiency, detection efficiency, screening strength, and yield.

20. **Reference Documents.** (See Section 2)

30. **Definitions and Acronyms.** (See Section 3)

40. **General Mathematical Relations.**

40.1 **Defect Density.** Under reasonable assumptions that the number of latent defects in a product are independently and identically distributed, the number of defectives in an equipment can be described by the Binomial Probability distribution, with parameters N and P.

Where:

N = total number of parts in the equipment

$\overline{P}$ = average part fraction defective over all part types

A part, as defined herein, is any identifiable item within the product which can be removed or repaired, (e.g., discrete semiconductor, resistor, integrated circuit, solder joint, connector). For large N and small P the Binomial can be approximated by the Poisson distribution with the parameter $D = N\overline{P}$

Where:

D = Defect Density (average number of latent defects per item)

The defect density $D = N\overline{P}$ can also be represented as:

$$D = N\overline{P} = \sum_{i=1}^{m} n_i p_i \qquad \text{(A-1)}$$

Where:

n_i = quantity of each part type i

p_i = defect density for each part type i

m = number of different part types

The procedures contained in Procedure B of Section 5, for obtaining planning estimates of defect density, are based upon the mathematical relations just described.

40.2 **Precipitation Efficiency.** The Precipitation Efficiency (PE) of a screen is expressed as the probability that the screen will precipitate a defect to a detectable state given that a defect susceptible to the screen is present. For ESS to be viable, the screening strength (and hence precipitation efficiency) of a screen must be independent of the number of defects and when the screen is performed. Mathematically this can be satisfied if the defects are exponentially distributed in time.

$$D_X = D_{LAT}(T)\,[1 - \exp(-k_1 t)] \qquad \text{(A-2)}$$

Where: D_X = defects precipitated

$D_{LAT}(T)$ = latent defect population at time T

k_1 = stress constant for precipitation

t = stress duration

Precipitation efficiencies for various screen parameters are given in Tables 5.14 through 5.17. Note: 1 - $\exp(-k_1t)$ yields precipitation efficiency as discussed in section 5.4.3.

40.3 **Detection Efficiency.** In general, Detection Efficiency can be represented by a Poisson Distribution in stress duration.

$$DE(t) = DE \times D_{PAT}[1 - \exp(-k_2t)] \qquad \text{(A-3)}$$

Where: DE = detection efficiency

D_{PAT} = existing patent defects

k_2 = stress constant for detection efficiency

t = stress duration

Provided the k terms for precipitation efficiency and detection efficiency are significantly different, the lower k term will dominate. With this simplification, detection efficiency can be considered to be independent of t and represented by the constant DE. Fixed parameters for calculating detection efficiencies are given in Procedure C in Part 5.

40.4 **Screening Strength.** The screening strength (SS) is defined as the product of precipitation efficiency and detection efficiency.

$$SS = PE \times DE \qquad \text{(A-4)}$$

40.5 **Yield.** Given prior estimates of p_i, equation A-1 can be used to estimate D_{IN}, the incoming latent defect density before assembly screening, since N and n_i are known for the assemblies and equipment to be screened. The remaining defect density $D_{REMAINING}$ can be described in a similar manner, except that the p_i, of equation 1, would be interpreted as the remaining part defect density. D_{IN} and $D_{REMAINING}$ are normalized quantities and can also be expressed as:

$$D_{IN} = \frac{\text{total number of latent defects introduced}}{\text{total number of equipment in the lot}}$$

$$D_{REMAINING} = \frac{\text{total number of latent defects remaining}}{\text{total number of equipment in the lot}}$$

Without an ESS program, a production lot of equipment will contain defects which are introduced into the equipments as escapes from previous part level screens and by poor workmanship or manufacturing processes. The defects introduced are expressed quantitatively as the average number of defects per equipment (D_{IN} or defect density). Using the Poisson probability distribution, the probability that an equipment is defective P(D) (i.e., contains one or more defects) is given by:

$$P(D) = 1 - \exp(-D_{IN}) \qquad \text{(A-5)}$$

The objective of an ESS program is to reduce D_{IN} to an acceptable level, say $D_{REMAINING}$, where $D_{REMAINING}$ is defined as the average number of defects remaining per equipment at delivery to the customer. Reducing D_{IN}

to $D_{REMAINING}$ also reduces P(D) so that:

$$P(D) = 1 - \exp(-D_{REMAINING}) \qquad (A\text{-}6)$$

(assuming all remaining defects will fail)

The probability that an equipment will pass a screening test is called Yield. Because not all remaining defects fail during the screen, the expression for yield becomes:

$$\text{Yield} = \exp(-D_{REMOVED}) \qquad (A\text{-}7)$$

If the Yield is specified as a goal, then $D_{REMOVED}$ can be determined by:

$$D_{REMOVED} = -\ln(\text{Yield}) \qquad (A\text{-}8)$$

and used as an objective for which an ESS program can be planned, implemented and subsequently monitored and controlled. Both $D_{REMAINING}$ and Yield are used in the handbook Procedures A and F, as the quantitative goal of the ESS program.

40.6 **Remaining/Removed Defects.** The quality of the ESS program and by extension, the number of defects removed is a function of five simultaneous effects:

- precipitation of latent defects;
- detection of precipitating defects (immediately and with stress time);
- detection of previously precipitated patent defects "immediately" due to different test or environment;
- detection of previously precipitated patent defects due to stress time;
- detection of "constant failure rate" defects

For mathematical purposes this can be reduced to three distinct terms:

- detection of previously precipitated latent defects;
- detection of latent defects precipitating during ESS;
- detection of defects precipitating at a constant rate i.e., determined by the limiting MTBF.

Therefore, the mathematical model can be represented by:

$$D_{REMOVED} = DE \times D_{PAT} + DE \times D_{LAT}[1 - \exp(-kt)] + DE \times CFR \times t \qquad (A\text{-}9)$$

Where:

DE = detection efficiency

D_{PAT} = patent defects

D_{LAT} = latent defects

k = stress constant

t = stress duration

CFR = constant failure rate

The remaining latent and patent defect density is given by:

$$D_{REMAINING} = (1 - DE)\,D_{PAT} + (1 - DE)\,D_{LAT}(1 - \exp(-kt)) + D_{LAT}(\exp(-kt)) \qquad (A\text{-}10)$$

40.7 **Chance Defective Exponential Model (CDE).** The CDE model is based upon the assumption that the population of parts within a lot of like equipments is comprised of two subpopulations, i.e., a main subpopulation of "good" parts and a much smaller subpopulation of defectives. The defectives contain major flaws which degrade with stress and time and are manifested as early-life failures. The failure rate of a defective part is several orders of magnitude greater than the failure rate of a "good" part. Therefore, relatively few defectives can dominate the reliability of the equipment during early product life.

Additional assumptions, terms and definitions which are used in the CDE model are:

(a) The number of defectives in an equipment is independent and identically distributed and the distribution is Binomial with parameters N and $\overline{P}$.

Where: N = total number of parts in an equipment
$\overline{P}$ = average part fraction defective

For large N and small $\overline{P}$ the Binomial can be approximated by the Poisson distribution so that $D = N\overline{P}$ is the average number of defects per item (defect density).

$$D = N\overline{P} = \sum_{i=1}^{m} n_i p_i$$

Where: n_i = quantity of part type i
p_i = fraction defective part type i

The defect density D is one of three parameters of the CDE model.

(b) The failure distribution of the "good" or main subpopulation of parts in an equipment is exponential with parameter λ_o and the reliability function is given by, $R_o(t) = \exp(-\lambda_o t)$. λ_o is another parameter of the CDE model. The parameter λ_o can also be expressed as $\lambda_o \equiv (N-D)\lambda_G$, where λ_G is the average failure rate of a "good" part

(c) The failure distribution of a defective part is exponential with parameter λ_D and the reliability function if given by $R_D = \exp(-\lambda_D t)$. The parameter λ_D is defined as the average failure rate of a defective part under a particular stress environment. Note that when the CDE model is applied to a screen, $(1 - R_D) = 1 - \exp(-\lambda_D t) = SS(t)$, the screening strength. Note that the average failure rate of a defective part is much greater than the average failure rate of a "good" part. i.e. $\lambda_D >> \lambda_G$ and with large defect densities the failure rate of the defective population can be greater than the population of "goods", i.e. $D\lambda_D > (N - D)\lambda_G$.

Given that a system contains n defective parts, the conditional reliability of the system $R_S(t/n)$ is:

$$R_S(t/n) X P(n) = R_o(t) \; X \; R_D(t)^n \qquad n = 0, 1, 2 \ldots$$

Using the Binomial, the joint probability of survival given n defects present is:

$$R_S(t/n) X P(n) = R_o(t)[R_D(t)]^n \binom{N}{n} p^n q^{N-n}$$

For large N and small P the Binomial can be approximated by the Poisson with parameter D = NP so that the unconditional survival probability for any number of defects m is given by:

$$R_S(t) = R_o(t) \sum_{m=0}^{\alpha} [R_D(t)]^m \frac{D^m \exp(-D)}{m!} \qquad \text{For all real values of m} \qquad \text{(A-11)}$$

Performing the summation in A-11 gives the reliability function:

$$R_S(t) = R_o(t)\exp[-D(1 - R_D(t)] \qquad \text{(A-12)}$$

Using the assumptions $R_o(t) = \exp(-\lambda_o t)$ and $R_D(t) = \exp(-\lambda_D t)$above; equation A-12 becomes:

$$R_S(t) = \exp\left[-\lambda_o t - D(1 - \exp(-\lambda_D t))\right] \qquad \text{(A-13)}$$

The failure rate for the system $\lambda_S(t)$ is given by:

$$\lambda_S(t) = -\frac{d}{dt}\ln R_S(t)$$

resulting in: $\lambda_S(t) = \lambda_o + D\lambda_D\exp(-\lambda_D t)$ (A-14)

The probability density function for the system is given by:

$$f_S(t) = \lambda_S(t) \times R_S(t)$$

so that: $f_S(t) = \left[\lambda_o + D\overline{\lambda}_D\exp(-\overline{\lambda}_D t)\right]\exp\left[-\lambda_o t - D(1 - \exp(-\overline{\lambda}_D t))\right]$ (A-15)

The expected number of failures for the system in time t is given by:

$$E_S(T) = \int_0^T t^{*}f_S(t)dt$$

which gives: $E_S(T) = \lambda_o T + D(1-\exp(-\lambda_D T)$ (A-16)

40.8 Relating DR to Field Reliability and Failure Rate. Using the CDE model the reliability and failure rate of a system which has not had ESS exposure during manufacture is given by equations (A-13) and (A-14) as:

$$R_S(t) = \exp\left[-\lambda_o t - D_{IN}(1 - \exp(-\lambda_D t))\right]$$

$$\lambda_S(t) = \lambda_o + D_{IN}\lambda_D\exp(-\lambda_D t)$$

λ_D is viewed as the failure rate of a defective under the field stress conditions to which the system will be exposed and λ_o is the limiting MTBF based on experience data.

Given the same system which has been exposed to ESS during manufacture, then D_{IN} is reduced to $D_{REMAINING}$ and the other model parameters λ_o and λ_D have the same interpretation as before. The failure rate function (equation A-14) both with and without an ESS program is illustrated in Fig A-1.

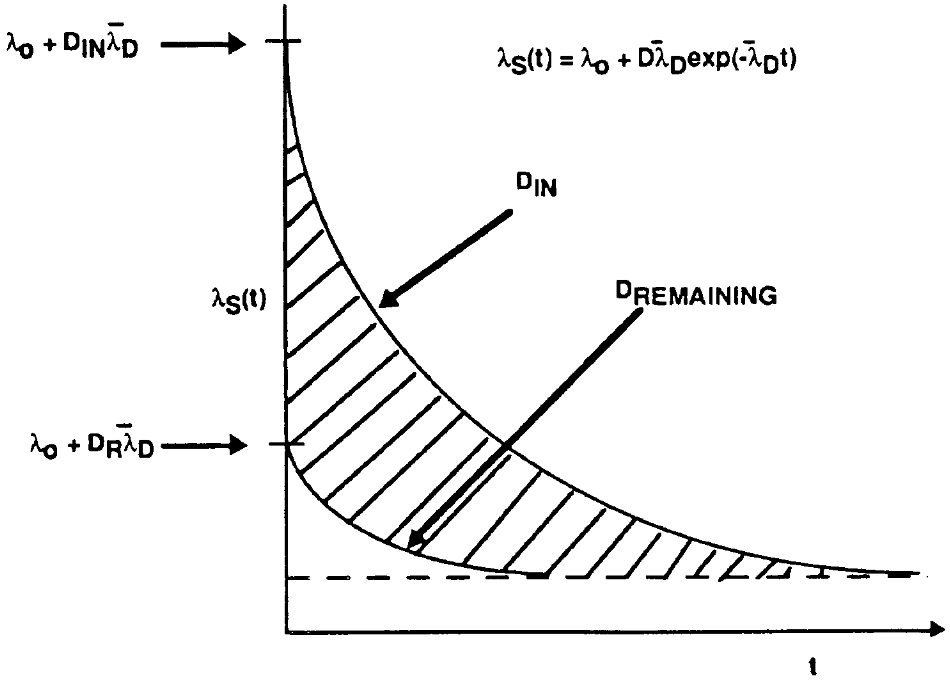


Figure A-1: Field Failure Rate vs. Defect Density

The shaded area represents the defects removed from the product as a result of the ESS program conducted during manufacture.

APPENDIX B

Product Reliability Verification Test

10. **General.** A product reliability verification test (PRVT) provides a means of establishing a reasonable level of confidence that the outgoing equipment is adequately free of defects and will achieve the required reliability in the intended application. The PRVT segment of the ESS program is primarily of use when the preceding ESS has been nearly eliminated through corrective actions that have reduced the incoming defect densities for parts and manufacturing. Since the PRVT is part of the ESS program the normal monitor and control procedures apply. For simplicity, it is useful to use the first pass PRVT yield as a reliability indicator.

20. **Reference Documents.** See section 2

30. **Definitions and Acronyms.** See section 2

40. **General Mathematical Relations.**

40.1 **Derivation.** The objective is to establish a mathematical relationship between PRVT yield and field reliability.

From Appendix A : $\text{Factory Yield} = \exp(-D_{REMOVED})$ (B-1)

$$D_{REMOVED} = DE[D_{PAT} + D_{REMAINING}*(1-\exp(-kt)) + CFR*t] \qquad \text{(B-2)}$$

The field failure rate FR is the defects removed in a time interval t divided by t ;thus,FR can be expressed as follows:

$$FR = \frac{D_{PAT} + D_{REMAINING}*(1-\exp(-kt)) + CFR*t}{t} \qquad \text{(B-3)}$$

since DE=1 for the field.

The failure rate for latent defects under field stress conditions is thus:

$$FR = \frac{D_{REMAINING}*(1-\exp(-kt))}{t} \qquad \text{(B-4)}$$

Since the field and factory defects are related by the stress adjustment factor:

$$SAF = \frac{\text{Latent Defects At Field Stress}}{\text{Escaping Latent Defects At Factory ESS Baseline Stress}} \qquad \text{(B-5)}$$

therefore, the field failure rate due to latent defects is related to the remaining defects at factory baseline stress according to:

$$FR = \frac{SAF*D_{REMAINING}*(1-\exp(-kt))}{t} \qquad \text{(B-6)}$$

The defects removed during PRVT is given by:

$$D_{IN}[PRVT]*SS[PRVT]$$

Thus the remaining defects as a function of the defects removed is given by:

$$D_{REMAINING}(\text{PRVT stress}) = \frac{D_{REMOVED}(PRVT)*(1-SS(PRVT))}{SS(PRVT)} \qquad \text{(B-7)}$$

Substituting SS=1-exp(-kt) and $D_{REMAINING}$ from equation B-7 gives the relationship between field failure rate and defects removed in PRVT

$$D_{REMOVED}(PRVT) = \left[\frac{\exp(-kt)}{1 - \exp(-kt)}\right]\left[\frac{FR^{*}T}{SAF[1 - \exp(-kt)]}\right] \qquad (B\text{-}8)$$

Using the relationship Yield= exp(-$D_{REMOVED}$) and defining MTBF(latent)=$\frac{1}{FR(Latent)}$ gives the desired relationship

$$Yield(PRVT) = \exp\left[\frac{-\left[\frac{\exp(-kt)}{1 - \exp(-kt)}\right]^{*}t}{SAF^{*}(1 - \exp(-kt)^{*}MTBF)}\right] \qquad (B\text{-}9)$$

The values for SS or alternatively the precipitation factors for PRVT (k) and the field (k) can be determined using Procedure C.

APPENDIX C

Fault Coverage Data

Tables C.1 and C.2 provide fault coverage estimates for various automatic test systems used by electronics system manufacturers. Fault coverage estimates are defined for specific fault types, eg. digital "stuck at 1 or 0" and do not represent the complete fault spectrum. Application usage and situation sensitive faults must also be considered. Thus, the values provided in Table C.1 and C.2 are a guide and should be used with caution.

Table C.1: Fault Coverage vs Test Types

Level Of Assembly	Test Type	Fault Coverage
Assembly	Production Line GO-NO GO Test	0.85
	Production Line In-Circuit Test	0.90
	High Performance Automatic Tester	0.95
Unit	Performance Verification Test (PVT)	0.90
	Unit Factory Checkout	0.95
	Final Acceptance Test	0.98
System	On-Line Performance Monitoring	0.90
	System Factory Checkout Test	0.95
	Customer Final Acceptance Test	0.99

Table C.2: Fault Coverage For Automatic Test Systems

Circuit Type	Automatic Test System Type			
	Loaded Board Shorts Tester (LBS)	In-Circuit Analyzer (ICA)	In-Circuit Tester (ICT)	Functional Board Tester (FBT)
Digital	45% to 65%	50% to 75%	85% to 94%	90% to 98%
Analog	35% to 55%	70% to 92%	90% to 96%	80% to 90%
Hybrid	40% to 60%	60% to 90%	87% to 94%	83% to 95%

As can be noted from the tables, using only a Functional Board Tester (FBT) provides 95% fault coverage but combining an In-Circuit Tester (ICT) with the FBT increased coverage to 97% and adding an In-Circuit Analyzer (ICA) to the sequence, increases coverage to 99%.

An illustration of fault coverage for a sample of 1000 PWA's subjected to various test strategies is also provided in Table C.3. The strategies employed include the use of each of four automatic testers independently and in combination.

Table C.3: Fault Detection for a 1000 PCB Lot Size

Fault Classification	Actual	LBS	ICA	ICT	FBT	ICA-ICT	ICA-FBT	ICT-FBT	ICA-ICT-FBT
Shorts	261	261	261	261	261	261	261	261	261
Opens	5	5	5	5	5	5	5	5	5
Missing Components	30	-	25	28	25	29	27	29	30
Wrong Components	67	-	53	61	55	64	59	60	65
Reversed Components	28	-	26	23	25	27	28	25	28
Bent Leads	43	-	38	43	43	43	43	43	43
Analog Specifications	25	-	13	21	18	21	21	22	23
Digital Logic	27	-	-	20	27	20	27	27	27
Performance	26	-	-	-	26	-	26	26	26
Total No. Of Faults	512	266	421	462	486	470	497	498	508
Fault Coverage	100%	52%	82%	90%	95%	92%	97%	97%	99%
Fault Coverage Increase	-	-	-	-	-	2.2%	2.3%	2.5%	4.5%
Rejected PCB'S	398	223	345	370	385	374	391	393	394
Rework Yield	-	195	316	354	376	361	384	388	393
Undetected Faulty PCB'S	-	203	82	44	22	37	14	10	5
Rework Yield	-	49%	79%	89%	94%	91%	96%	97%	99%
Rework Yield Increase	-	-	-	-	-	2%	2.1%	3.2%	4.5%
Finished Units		805	918	956	978	963	986	990	995

The faults detected are typical patent defects and do not cover the spectrum of defect types of interest in stress screening. The statistics provided in the table, however, provide a basis for developing estimates of detection efficiency when a stress screening program is being planned. The data should also be helpful in selecting test strategies for use with stress screens.

Custodians:
Army - CR
Navy - EC
Air Force - 17

Preparing Activity:
Air Force - 17
Project No. RELI-0031