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ELECTRONIC EQUIPMENT SCREENING AND DEBUGGING TECHNIQUES

R. E. Schafer
S. P. Gray
L. E. James
E. A. McMillan

Hughes Aircraft Company

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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APPROVED:

EUGENE FIORENTINO
Project Engineer

APPROVED:

JOSEPH J. NARESKY
Chief, Reliability & Compatibility Division

FOR THE COMMANDER:

JOHN P. HUSS
Acting Chief, Plans Office

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a quantitative investigation into the optimum selection of screening and debugging methods for the purpose of removing defects, and hence improving reliability, throughout the development process.

A computerized optimization model has been developed which can be used to address three problem areas;

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i) Select an optimum sequence of screens for a fixed dollar expenditure,

ii) Select a sequence of screens which minimizes costs in the face of a fixed desired reliability improvement, and

iii) Provide quantitative relationships for performing screening/debugging tradeoffs.

In order to implement the model it was necessary to obtain data to compute test strengths and test costs. The model includes four assembly levels, five types of screens (temperature cycling, constant temperature, vibration constant power and power cycling), provides for introduction of defects at each assembly level and includes the rework cycle.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (Continued)

EVALUATION

1. The objective of this study was to develop techniques which permit cost/effectiveness trade-off analyses among various screening test approaches that may be used during the development and production of electronic equipment.

2. The objectives have been satisfactorily achieved. A computerized optimization model was developed for use as a decision tool in selecting the most cost-effective test sequence from among the many possible alternatives that are presented in a given program. Although the model is rather complex, the computer program allows for optional user input and relative ease in performing sensitivity and trade-off analyses.

3. Use of the model is recommended as an aid in selecting optimum test sequences in terms of minimum expected test and rework costs and maximum screening effectiveness. In addition, users of the model are encouraged to provide feedback information which will permit further refinements in the model structure, input parameters and application procedures.

Eugene Fiorentino

EUGENE FIORENTINO
R&M Engineering Techniques Section

SECTION 0.0 – INTRODUCTION

One of the key ideas developed in reliability engineering is the realization that electronic parts, cards, assemblies, equipments and systems contain defects, due to a variety of causes such as poor parts, design errors and manufacturing errors among others, which are not readily detectable by the usual electrical tests of functional performance. Moreover, the later in system development and system use that the defects are uncovered the more costly the discovery becomes. Of course this last statement must be balanced by the fact the removal of all defects at one level (e.g., parts) does not guarantee no defects at the next (e.g., card) level because in each step of the assembly process new defect causes are introduced.

It is now a truism that by subjecting parts, cards, assemblies, equipments and systems to extremes of environment such as temperature or vibration, these previously mentioned undetectable (by common means) defects can be degraded to a detectable level and with an appropriate test setup can be detected and eliminated. These kinds of tests with the purpose of eliminating undetectable or latent defects are generally called screening or debugging (SD) tests.

Unfortunately there are a large number of possible tests that can be run in any particular situation and the methodology for selecting an optimum sequence of tests is not well developed: irrespective of whether one's standard of methodology is good applied science or even good engineering.

The purpose of this present study is to develop a computerized screening and debugging optimization (SDO) model which includes test strength (TS) and test costs among the primary variables and which can be used to solve three problems:

1) For a fixed dollar amount available what is the optimum sequence of screens which yields the highest final MTBF, θ_F.

2) In the face of an initial MTBF, θ_I and a θ_F requirement determine the sequence of screens which moves the "system" from θ_I to θ_F, $\theta_I < \theta_F$, at least cost.

3) For a fixed sequence of screens, determine the cost and the test strength.

In order to solve these problems it was necessary to:

1) Perform a literature search to determine what types of screens are useful and feasible.

2) Build a data base in order to compute test strengths (TS) and test costs.

3) Find a way of converting MTBF to defects.

4) Construct a flexible, useful computerized model which truly reflects the process of and cost of removing defects from a system at its various stages or levels of assembly.

The balance of this report discusses how these four tasks were accomplished and what results were achieved.

SECTION 1.0 – SUMMARY OF RESULTS

The basic result of the study is the model itself. It is a fairly sophisticated model yet, hopefully, it will be useful. Its utility derives partly from the fact that it is a faithful representation of the screening process: it includes rework cycles, test strengths, test cost models, allows for introduction of defects when a new level of assembly is reached and accommodates imperfect rework at the card and assembly levels. It includes four levels of assembly: card, unit, equipment and system. The reasons for omitting the part level are thoroughly discussed in Section 3.3. It accommodates temperature cycling, constant temperature, vibration, constant power and cycled power screens.

Perhaps the key feature of the model is that practically all the required input variables are already included in the model as fall-back options. That is, if the user has better information for some variables he can enter it; otherwise the model uses what we have put in it. The model is described in considerable detail in Section 5.0. However, the accompanying Table 1.1 gives a good idea of the parameters needed in the model and how the fall-back option is implemented.

There are three major test characteristics: test costs, screening strength and detection probability. The equations yielding screening strength (SS) are incorporated in the model. No fall-back option is provided. If the user desires to change the SS equations the model should be changed. Because the fixed costs of test are so highly user dependent (e.g., how is the test equipment being amortized) this variable is a user input with a zero fall-back option. The variable test costs are also a user input with functions provided in the model as a fall-back option. Detection probability is also a user input with a fall-back option of 0.75.

For the manufacturing data required all inputs are user inputs with the exception of the fixed portion of rework cost. This cost is programmed as a function of variable costs and no fall-back option is provided.

The program data portion of the input parameters consists of all user inputs with fall-back options provided for each parameter. Here "tolerance" is necessary to decide when a solution has been reached.

The output reports consist of the optional test sequence, including test parameters (e.g. 14 temperature cycles) total cost broken down by level and by test and the total TS.

TABLE 1.1. **Input Data Requirements/Options for SDO Model**

Data Requirements	Input	Fall-Back Option
Test Characteristics		
– Fixed Test Cost	• User	• Assume zero
– Variable Test Cost	• User	• Provided as function of test
– Screening Strength	Computed	
– Detection Probability	• User	• 0.75 for all tests
Manufacturing Data		
– Fixed Rework Cost	• Function of Variable Cost	• None
– Variable Rework Cost	• User	• Provided as function of rework level
– Fraction Defectives to "Card" Rework	• User	• Provided as function of rework level
– Fraction Detectives Removed at Card Rework	• User	• 0.5
– Fraction Defectives Removed at Assy Rework	• User	• 0.5 All levels
Program Data		
– Total Quantity of Parts	• User	
– Percentage Parts – Defects	• User	• 1.0 percent of total parts
– Percentage Assy – Defects	• User	• 2.3 percent of total parts
– Number of Assy Levels	• User	• (4 – levels max/min)
– Tolerance (E)	• User	• 1 percent

TABLE 1.1. Input Data Requirements/Options and Output Report for SDO Model (Cont)

- Input Data Summarized
- Output Report
  - Optimal Test Selection
  - Test Parameter Values
  - Total Cost by Level by Test
  - Total Test Strength

Test Sequence	Parameter Value				Cost
	No. 1	No. 2	No. 3	No. 4	
Level 1					
Test 1					
•					
•					
•					
Level 2					
Test 1					
•					
•					
•					
Total Cost					

SECTION 2.0 – DATA SOURCES

2.1 Literature Survey

The literature survey was conducted in order to ascertain state-of-the-art popular screens, costs, and test strengths. Little data was obtained for the variables test costs and test strengths because the data available was stated in qualitative rather than quantitative terms.

The literature survey itself consisted of obtaining literature searches from the Hughes library, National Aeronautics and Space Administration Scientific and Technical Information facilities, and the Department of Defense Documentation Center. Articles thought to be applicable to the study were reviewed and further segregated by their relevancy. The final results yielded approximately fifty (50) articles/reports of particular relevance to this study. A complete listing of the references and bibliography can be found in Section 8.0.

Several reports were detailed enough, i.e., references 51 and 52, to be incorporated into the study's main data base.

Other reports suggested guidelines to follow for specific screening procedures. For example, reference 8 supplied the following proposed guidelines for temperature cycling acceptance testing of electronic assemblies:

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

Temperature Range

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

Temperature Rate of Change

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

Temperature Soak Times

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

Equipment Operation

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

Equipment Monitoring

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

Failure Criteria

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

Reference 51 gives a hypothetical circuit card screening program as follows, based on its experiments with a single card type:

Rated power would be applied to the cards while they were thermally cycled between temperature extremes at a rate of ±20°C/min. The temperature profile would be sawtooth (i.e., no dwell). Power would not be cycled and the cards would not be vibrated. The temperature rate chosen (20°C/min) would cause the least solder-cracking while permitting completion of screening in the fastest possible time. The number of temperature cycles chosen would depend upon the estimated number of quality and reliability failures contained in the population, and the subsequent reliability requirement.

Reference 24 drew the following conclusions concerning the relationships between screens and field reliability.

- Those items that had the more effective burn-in testing on production units tended to have the better reliability agreement. This indicates the necessity for adequately specifying a production unit burn-in both in duration and in environmental exposure.

- Relationships were found between reliability differences and several temperature related measures for ambient cooled WRA's, including:

  - minimum ambient temperature
  - operating time at low temperature
  - maximum ambient temperature
  - temperature rate of change

  indicating that the current MIL-STD-781 tests of only requiring dwells at the temperature extremes with moderate rates of change between the limits is not an adquate test. No provisions exist for evaluating the item under conditions of rapid and frequent temperature cycling.

- The significant relationships between vibration measures and reliability differences included:

  - level
  - duration

indicating that the MIL-STD-781 vibration test of requiring 10 minutes of sinusoidal vibration each hour at one non-resonant frequency between 20-60 Hz is not representative of the field environment. The test article is never exposed to those frequencies occurring in the field, that produce failures. The vibration test duration was found to be a poor representation of the accummulated field vibration time. The lack of reliability agreement was more pronounced in WRA's installed in jet aircraft where the field environment is random.

The majority of the articles dealt in generalities concerning screen effectiveness. The screens discussed varied, but could be classified into operating, environmental, e.g., temperature, vibration, and a combination of the two. The conclusions and experiences of the articles were used accordingly in the development of the concepts utilized in this report.

General conclusions can be expressed in the words of Reference 1: "The one central theme that emerges ... is that opinions and case histories vary widely within and between the product lines ...".

A summary of the literature search can be found in the following section.

2.2 Summary of the Results of the Literature Survey

At the outset we must distinguish between accelerated tests in general and the screening/debugging tests of interest in this present study. Generally, accelerated tests have as their purpose the extrapolation of some reliability measure "back" from accelerated conditions to normal conditions, the motivation being that testing at normal conditions takes too long to provide statistically reliable estimates of whatever measure of reliability is selected. The purpose of screening and debugging tests is the elimination of (previously) undetectable defects.

As previously indicated the purpose of this present study is to create a model with which to optimize the screens used. For this reason the key issues for any particular screen for this study are:

- the test strength (TS) of a screen: the probability that a (previously) undetectable failure will be detected by the screen.

- the costs of the screen.

While there are literally tons of material on screening and debugging tests the literature search turned up very little data regarding the above two factors. This is not surprising since if much data existed this present study would probably not be needed. A mathematical model is a very demanding beast and cannot accept inputs like: "about 10-12 thermal cycles should do it" (see reference 8). It demands inputs like: the TS for this screen is 0.73.

However, the literature search was valuable in pointing out what screens are likely to be of use in eliminating defects and actually there is little disagreement on the matter. The useful screens appear to be:

i) temperature cycling
ii) constant temperature "soak"

iii) power applied continuously
iv) power cycled
v) vibration
vi) various combinations of these.

Before discussing these tests an important issue must be put in perspective: do screening tests damage good items (parts, cards, assemblies, etc.)? The general consensus from the literature search is that screens do not damage good items if the screens are used within reasonable limits. It is obvious, of course, that beyond "reasonable" limits damage could occur although the literature is, more or less, silent on what the absolute limits are. For this present study the matter is of little consequence. The SDO model is concerned with the removal of defects by screens. Test strength is defined as the (conditional) probability of detecting a latent defect. The fact that good parts may also be removed affects only the costs of the screen and if the user (of the SDO model) has a feel for this probability (of damaging a good item) he can factor it into his cost model.

The overwhelming majority of the literature regards temperature cycling as the most powerful (without regard to cost) and versatile screen; it being claimed that temperature cycling screens can detect part defects, workmanship defects and design errors. The three key variables (all of which affect TS and costs) of a temperature cycling test are

i) number of cycles
ii) rise time: rate of change of temperature with respect to time
iii) temperature extremes

The literature indicates that on the order of 10 cycles are used for parts/cards and on the order of 25 cycles for assemblies and equipments. Rise times vary from about $1^{o}C$/minute to something like $10^{o}C$/minute. The temperature extremes were commonly on the order of $-60^{o}C$ to $125^{o}C$.

Another popular screen is the constant (usually high) temperature soak. The two key variables of a constant temperature screen which relate to the TS and costs are the length of the soak and the temperature of the soak. The literature agrees that the same kind of defects can be eliminated by a constant temperature screen as can be eliminated by a temperature cycle screen although for equal times at equal temperatures the temperature cycle screen is thought to have a larger TS. There was no agreement at all in the literature regarding length of the constant temperature screen although 100 to 300 hours is common. Also, there is a belief, though no explicit expression of TS was found (except for the Hughes Aircraft internal work called CREDIT, reference 42) that time of soak and temperature level can be "traded off." For example, 1000 hours at $70^{o}C$ is equivalent to 200 hours at $125^{o}C$ in TS. Obviously there is a tradeoff since TS is a function of soak time and temperature used. That is, TS is a function of two variables and in 3-dimensional space (TS, soak time, temperature) the relationship is a surface which might have many common points TS. Generally it is agreed that for electronic items defects are not detected, that is, TS is low, until about $50^{o}C$ is used. On the other hand, anything over about $125^{o}C$ and certainly $200^{o}C$ begins to damage good parts.

Power application is another popular screen even though by itself long times or number of cycles are required to obtain even a moderate TS. Also it is agreed cycled power is more effective than continuously applied power for equal amounts of time applied. Notwithstanding the low TS, many system level screens like RPM or Duane growth control programs are essentially power screens on large systems. Thus power screens are most effective in detecting the failure of an item to perform a function because of a design error rather than detecting bad parts or poor (as against incorrect) workmanship.

One of the more useful applications of power screens is in conjunction with temperature screens. When a part or card is operated at high temperature, probable surface contamination problems are often forced to a detectable level. This is an Arrhenius type effect. When a bias voltage is applied during high temperature screens, latent defects can be identified. This is the so-called Eyring effect.

Vibration is the final popular screen that is often used. The consensus seems to be that vibration should be random and that vibration is extremely useful for detecting solder joint, lead, connection and bond problems. There was no agreement at all on the length of the cycle or number of cycles but on the order of about 1-20 cycles was common. The levels ranged from 1g or 2g's to about 6g's.

Various combinations of the above screens can be used very effectively to locate just about any kind of latent defect. In fact, the screens used and the levels of the variables is a cost/TS tradeoff and this is what the SDO model does.

2.3 Industry Survey

2.3.1 Questionnaire

Several approaches were discussed concerning the industry questionnaire. The final approach taken was that of a two (2) page survey which could develop the data necessary to the purposes of this study in a cost-effective manner. A copy of the questionnaire, along with the guidelines, Figures 2.1, 2.2, follow.

The response to the survey was good. A total of forty-two (42) data points was obtained from 64% of the respondents to the questionnaire. The total response to the two hundred (200) questionnaires distributed was 17%. This response is considered good in comparison to the results of other surveys trying to obtain similar information, i.e., Reliability Study Circular Electrical Connectors, RADC-TR-73-171, which obtained 21% response out of 600 surveyed, and the Bayesian Reliability Demonstration, RADC TR-71-209.

Cost data was obtained in 67% of the responses, which was good considering its proprietary nature, while some form of screen effectiveness data was found in 93% of the cases. Data was gathered at the part, card, and higher assembly levels. The distribution of the data is shown in Table 2.1.

- THE MAIN POINTS OF INTEREST ARE:
  - describe the screen as well as possible (section 4)
  - describe the effectiveness of the screen (section 5)
  - estimate costs (section 6)
- DO NOT BE RELUCTANT TO MAKE ESTIMATES
- DO NOT BE RELUCTANT TO LEAVE BLANKS

  For example, in section 6 if only estimated total costs are available, do not worry about fixed and variable costs.

Figure 2.1. Guidelines For Screening/Debugging Form

HUGHES AIRCRAFT COMPANY

FULLERTON CALIFORNIA 92634

SCREENING & DEBUGGING TEST DATA FORM

1. NAME OF PERSON COMPLETING FORM__________DATE COMPLETED______

ORGANIZATION (WITHIN COMPANY)______________________

2. SCREENED/DEBUGGED (S/D) ITEM DESCRIPTION:

2.1 PART____CARD____ASSEMBLY____EQUIPMENT____OTHER__________

2.2 PART QUALITY LEVEL PROCURED: COMMERCIAL____JAN____883____OTHER____

2.3 ITEM NAME(e.g., I.C., Diode, Motor, etc.)____TYPE OR FUNCTION____

2.4 QUANTITY TESTED____COMPLEXITY OF ITEM; NO. OF PARTS________

2.5 PARENT "SYSTEM" NAME/TYPE______________________

3. TEST BACKGROUND

3.1 WHY WAS THIS ITEM SELECTED FOR SCREEN__________________

3.2 PROGRAM PHASE: DEVELOPMENT____PRODUCTION____OTHER________

3.3 WAS A FORMAL RELIABILITY DEMO TEST REQUIRED ON THE OVERALL PROGRAM

3.4 PURPOSE OF SCREEN DETECT:

QUALITY DEFECTS__________MANUFACTURING DEFECTS________

DESIGN ERRORS__________OTHER__________________

4. TEST DESCRIPTION

4.1 TEST DATES: START__________END__________

4.2 TEST CONDITIONS:

4.2.1 SCREENING STRESS(ES) USED__________________

(E.G. TEMPERATURE, VIBRATION ETC.)

IF MORE THAN ONE TYPE OF STRESS, GIVE SEQUENCE________

4.2.2 MAX STRESS, MIN STRESS, RISE/DWELL TIME WHERE APPLICABLE

FOR EACH STRESS USED__________________

FIGURE 2.2

4.2.3 LENGTH OF STRESS CYCLE (HOURS)______NUMBER OF CYCLES______

4.2.4 STRESS EXCEED RATED REQUIRED: YES__________NO____________

% EXCEED RATED/NOMINAL________________________________

4.2.5 POWER APPLIED DURING TEST: CONTINUOUSLY____PERIODICALLY____

NO POWER__________

4.2.6 APPLIED POWER EXCEED RATED: YES__________NO____________

% EXCEED RATED/NOMINAL________________________________

4.3 PREDOMINANT FAILURE MODES/MECHANISMS OBSERVED:________________

5. EFFECTIVENESS OF SCREEN

5.1 PASS/FAIL CRITERIA: EXCEED RATINGS_____DRIFT_____OTHER__________

5.2 ITEM ELECTRICALLY TESTED BEFORE SCREEN: YES___NO___% DEFECTIVE____

5.3 % DEFECTIVE (REJECT RATE) AFTER SCREEN__________________________

5.4 ESTIMATE % IMPROVEMENT (OVER UNSCREENED MTBF) IN ITEM MTBF_______

5.5 ESTIMATE % IMPROVEMENT (OVER UNSCREENED) IN % DEFECTIVE_________

5.6 DO YOU FEEL THE SCREEN WAS WORTH THE MONEY: YES_______NO________

5.7 DO YOU FEEL THE SCREEN DESTROYED A SIGNIFICANT % OF GOOD ITEMS:

NO_______YES_______ % GOOD ITEMS DESTROYED_______

6. COST OF SCREEN (DOLLARS)

6.1 VARIABLE_______________FIXED_______________TOTAL_______________

6.2 COST PER ITEM SCREENED: VARIABLE_______FIXED_______TOTAL_________

6.3 COST PER DEFECTIVE FOUND: VARIABLE_____FIXED_______TOTAL_________

7. SEND ME A COPY OF THE FINAL REPORT (ADDRESS)______________________

8. REMARKS

FIGURE 2.2 (cont'd)

TABLE 2.1 Survey Data Distribution

Total Response 17% (34/200)			
Test Level		Test Data	Cost Data
Part	24%	100%	60%
Card/Module	12%	80%	20%
Equip/System	64%	93%	78%

The responses of the questionnaire were of major import in the developing and modeling of test strengths as defined in Section 3.4, as well as supplying "state-of-art" information concerning screening and debugging techniques.

2.3.2 Companies Contacted

Distribution of the questionnaire was made by obtaining a list of responsible contacts who could supply the study with reliable data. It was decided that the GIDEP (Government-Industry Data Exchange Program) Roster of Representatives, in addition to several personal contacts of study personnel, could provide such required data.

The companies chosen were felt to be representative of the "industry". Several divisions of the larger corporations were contacted in hopes of comparing the data for standardization of costs, etc., however, results in this regard were insufficient.

Table 2.2 is the listing of companies chosen for distribution of the questionnaire.

2.3.3 Survey Data

Out of the forty-two (42) data points supplied by the industry survey, thirty-four (34) were found to be sufficient to determine test strengths for their respective screens.

Due to several referenced screen parameters being identical, a total of seventeen (17) different test strengths were determined. The following Table 2.3 presents the data obtained from the industry survey and their respective test strengths. These test strengths were computed from the equations given in Section 4.2.

TABLE 2.2 Companies Contacted

Aerojet Electrosystems Co.
Aeronutronic-Ford Corp.
Aerospace Corp.
Ail Cutler-Hammer
Avco Corp, Systems Div.

Beckman Instruments
Bell Aerospace Co.
Bendix Corp., Guidance Systems Div.
Bendix Corp., Aerospace Sys Div., Mishawaka Operation
Bendix Corp., Aerospace Sys Div.
Booz-Allen Applied Research Inc.
Boeing Aerospace Company
Bulova Watch Co.
Bunker-Ramo Corp.

Celesco Industries Inc.
Chrysler Corp.
Cincinnati Electronics Corp.
Control Data Corp.
Crane Co.
Cubic Corp.
Curtiss Wright Corp.

Dalmo-Victor Co.
Delco Electronics
Delco Electronics Div., General Motors Corp.
Digital Equipment Corp.
Douglas Aircraft Co.

Electro Optical Systems Inc.
Electronic Communications Inc.
Electrospace Systems Inc.
Emerson Electric Co.
EMR-Telemetry, Weston Instr.
EPSCO Inc.
E-Systems Inc

Fairchild Hiller Corp.
Fairchild Republic Co.
Fairchild Space & Defense Systems Div.
Fairchild Stratos Div.
FMC Corp.
Foxboro Co.

General Atomic Co.
General Dynamics Corp., Electro Dynamics Div.
General Dynamics Corp., Electronics Div.
General Electric Co., Research & Development Center
Goodyear Aerospace Corp.
Grumman Aerospace Corp.
GTE Sylvania Inc. Elect Systems Group, Western Div.
GTE Sylvania Inc. Elect Systems Group, Eastern Div.

Harris Corp.
Harris RF Communications Inc.
Hartman Systems Div. A-T-O Inc.
Hazeltine Corp., Electro-Acoustic Lab
Hazeltine Corp., Electronics Div.
Hercules Inc.
Hermes Electronics LTD.
Hewlett Packard Co.
Hittman Assoc. Inc.
Hoffman Electronics Corp.
Homes & Narver Inc.
Honeywell Inc., Marine Systems Center
Honeywell Inc.
Honeywell Inc. Aerospace Div.
Honeywell Information Sys Inc.
Honeywell Inc., Govt & Aeronaut Prod Div.
Honeywell Radiation Center

IBM Corp.
IBM Corp., Electronics Systems Center
Interstate Electronics Corp.
Itek Corp.
ITT Aerospace/Optical Div.
ITT Avionics
ITT Federal Electric Corp
ITT Gilfillan Inc.

Jet Propulsion Laboratory

Kaiser Aerospace & Elec Corp.
Klauder, Louis T & Assoc.
Kollsman Instrument Corp.

TABLE 2.2 Companies Contacted (Cont)

Lawrence Livermore Lab.
Leeds & Northrup Co.
Life Systems Inc.
Little. Arthur D. Inc.
Litton Data System Div.
Litton Systems Inc.
Lockheed California Co.
Lockheed Electronics Co.
Lockheed Georgia Co.
Lockheed Missiles & Space Co., Space Systems Div.
Lockheed Missiles & Space Co., Missile Systems Div.
Loral Electronics Corp.

Martin Marietta Corp.
Martin Marietta Aerospace
Martin Marietta Aerospace
McDonnell Douglas Astronautics Co, West
McDonnell Douglas Electronics Co.
Mechanics Research Inc.
Motorola Inc.

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Pacific Car & Foundry Co.
Parker Hannifin Corp.
Parsons Co.
Perkin-Elmer Corp.
Plessey Industries Inc.

RCA Astro Electronics Div.
RCA, Aerospace Systems Div.
RCA, Govt & Comm. Sys.
RCA, Missile & Surface Radar Div.
Raytheon Co., Electro Magnetic Sys. Div.
Raytheon Co., Missile Systems Div.
Raytheon Co. Lever Bldg.
Raytheon Co. Equipment Div.
Reflectone Inc.
Rel-Reeves Inc.
Rexnord Inc.
Rockwell International Electronics Operations
Rockwell International Rocketdyne Div.
Rockwell International Space Div.
Rockwell International Collins Radio Group Electronics Oper DI
Rockwell Internationall Collins Radio Group Electronics Oper DI
Rockwell International Columbus Aircraft Civ.
Rockwell International Collins Radio Group
Rohr Industries

Sanders Associates
Sandia Laboratories
Sangamo Electric Co.
Science Applications Inc.
Science Applications Inc.
Scott Electronics Corp.
Sedco Systems Inc
Sierra Research Corp.
Singer Co.
Singer-Kearfott Div.
Solar Div.
Sperry Marine Systems Div.
Sperry Microwave Electronics
Sperry Rand Corp., Sperry Flight Sys. Div.
Sperry Rand Corp. Systems Mgt. Div.
Sperry Rand Corp., Sperry Systems Mgt.
Stencel Aero Engineering Corp.
Stone & Webster Engineering Corp.
Stromberg Carlson Corp.
Stromberg Datagraphix Inc.
Systematics General Corp.
Systems Associates Inc.
Systems Evaluation Inc.

Tektronix Inc.
Teledyne Cae
Teledyne Ryan Aeronautical
Teledyne Systems Co.
Texas Instruments Inc.
Tracor Inc.
TRW Equipment Group
TRW Systems Group
TRW Colorado Electronics Inc.

Unidynamics
Union Carbine Corp.
Union Switch & Signal Div.
United Engineers & Constructors Inc.
United Nuclear Industries Inc.
United Technologies Corp., Norden Div.
United Technologies Corp., Hamilton Standard Div.
Univac, Div of Sperry Rand

TABLE 2.2 Companies Contacted (Cont)

Value Engineering
Vega Precision Laboratories Inc.
Vitok Engineers Inc.
Vought Corp., Michigan Div.
Vought Corp., Systems Div.

Westinghouse Electric Corp., Marine Div.
Westinghouse Electric Corp., Def & Elect Sys. Center
Westinghouse Electric Corp., Industrial Equipment Div.
Westinghouse Electric Corp., Astronuclear Lab
Weston Instruments Inc.
Weston Instruments Inc.
Wiggins EB

Zimmer - USA

TABLE 2.3 Industry Survey Data

Time is Expressed in Hours
Temp is Expressed in $^{\circ}C$

Respondent Number*	Constant Temp Cyc**, Temp, Time	Cycled Temp Cyc, Temp Rate, Hi, Lo	Vibration Cyc, g's, Time Temp	Constant Power Cyc. Time	Cycled Power Cyc. Time	Test Strength
2; 30	1, 125, 168			1, 168		.3231
3; 10	1, 25, 168			1, 168		.2177
6	2, 55, 2			2, 8		.0278
8A;B	1, 25, 48			1, 48		.0713
29	1, 40, 144		12, 1, 1.3, 40		12, 12	.2163
38A	5, 125, .167	5, 12.5, 125, -40				.3224
38B	1, 25, 96			1, 96		.1348
4	14, 72, 5.5 14, -54, 2.5	14, 5, 72, -54	14, 2, .83, 72			.3512
5		60, 5, 100, -40				.5746
7	1, 60, 2 10, 60. .25 10, -40, .25	10, 20. 60, -40				.4869
8C; 12-25	8, 55, 2	8, 5, 55, -54	8, 2.2, .33, 55		8, 2.73	.2080
28	18, 55, 2 18, -54, 2	18, 5, 55, -54	18, 2, .33, 55		18, 3	.3890
31	55, 80, 2 55, -55, .5	55, 3.8, 80, -55				.5742
34	12, 55, 5.5 12, -54, 2.5	12, 5, 55, -54				.2791
36	4, 60, 8 4, 0, 1	4, 3, 60, 0				.0666
37	24, 71, 24 24, -55, 24	24, 5, 71, -55				.6169
39	3, 55, 2	3, 5, 55, -55	3, 2.2, .33, 55		3, 2.37	.0863

*These numbers are the code used for the qu[illegible]ionnaire responses.

**Cyc at this level indicates the number of times the Constant Temp is executed.

2.4 Internal Data

2.4.1 Hughes - Fullerton

Much of the cost data used in the study was extracted from Hughes-Fullerton facilities. Due to the many and varied factors contributing to this cost data, an attempt was made to ascertain the needed information on a "typical" card, module, unit, and system level. This was accomplished through an averaging of costs associated with particular programs.

System data was collected from fourteen (14) on-going Hughes-Fullerton programs. Systems Effectiveness Department personnel supplied the study with data in the following fields; MTBF (specified, predicted, initial, final), operating time, environmental time/conditions, percent of non-standard to total number of parts, total number of subcontractors (on assembly level), complexity (part count) and Operations and Maintenance Reports (OMR's). Additional system level data was extracted from The Reliability Growth Study, Ref. 47, conducted at Hughes-Fullerton.

The in-house systems contributing the above mentioned data are:

CVTSC - Display Console
IPD - Shipboard Radar
LFR - Low Frequency Receiver
PRC 104 - Portable Radio
SID - Display Console
SLQ 31 - Electronic Warfare Sui.
TDMA - Communications Terminal
TPQ 36 - Mortar Locator Radar
TPQ 37 - Artillery Locator Radar
UYQ - Console
COMBAT GRANDE - Air Defense System
MK 31 - Weapon Control Console
MK 82 - Weapon Data Converter
SURTASS - Towed Sonar Segment

2.4.2 Additional Hughes Aircraft Sites

The Hughes sites that contributed to the study's main data base in addition to Hughes-Fullerton were Culver City, El Segundo, and Tucson. Supplementary cost data was obtained from El Segundo manufacturing personnel, screening strength equations were contributed by Culver City, while test effectiveness data was contributed by all three of these additional sites.

The programs/experiments contributed by these Hughes Aircraft Company sites consist of: F-15 Radar Control; Maverick; B-52; and F-15.

The following table 2.4 represents the test data obtained from these sources, combined with the test strengths computed from the test strength equations, Section 4.2.

TABLE 2.4 Hughes Internal Data

Time is Expressed in Hours
Temp is Expressed in ^{o}C

Reference	Constant Temp Cyc, Temp, Time	Cycled Temp Cyc, Temp Rate, Hi, Lo	Vibration Cyc, g's, Time, Temp	Constant Power Cyc, Time	Cycled Power Cyc, Time	Test Strength
F-15 Radar Control		24, 6, 115, -60				.5084
4 different tests – all at		72, 6, 115, -60				.5979
card level		120, 6, 115, -60				.6000
		168, 6, 115, -60				.6000
Maverick		12, 5, 75, -40				.2514
16 tests – First twelve		12, 10, 75, -40				.3975
at card level, remaining		12, 20, 75, -40				.5316
four at unit level		12, 5, 75, -40			12, .006	.2515
		12, 10, 75, -40			12, .006	.3976
		12, 20, 75, -40			12, .006	.5317
		48, 5, 75, -40				.5317
		48, 10, 75, -40				.5922
		48, 20, 75, -40				.5999
		48, 5, 75, -40			48, .006	.5318
		48, 10, 75, -40			48, .006	.5923
		48, 20, 75, -40			48, .006	.6000
		3, 10, 75, -40		3, .383		.1438
		12, 10, 75, -40		12, .383		.4006
		3, 20, 75, -40			3, .006	.2514
		12, 20, 75, -40			12, .006	.5317
B-52		64, 5, 80, -40	33, 6, .25, 25	64, .40		.5904
53 tests – all at card		64, 5, 80, -40	33, 6, .25, 25			.5786
level		64, 5, 80, -40	33, 6, .25, 25		64, .40	.5906
		64, 5, 80, -40				.5697
		64, 10, 80, -40	33, 6, .25, 25	64, .20		.6124
		64, 10, 80, -40	33, 6, .25, 25			.6068
		64, 10, 80, -40	33, 6, .25, 25		64, .20	.6124
		64, 10, 80, -40				.5984

TABLE 2.4 Hughes Internal Data (Cont)

Reference	Constant Temp Cyc, Temp, Time	Cycled Temp Cyc, Temp Rate, Hi, Lo	Vibration Cyc, g's, Time Temp	Constant Power Cyc, Time	Cycled Power Cyc, Time	Test Strength
B-52 (Cont) 53 *tests* – all at card level		64, 20, 80, -40	33, 6, .25, 25	64, .10		.6111
		64, 20, 80, -40	33, 6, .25, 25			.6082
		64, 20, 80, -40	33, 6, .25, 25		64, .10	.6111
		64, 20, 80, -40				.6000
		168, 5, 80, -40	33, 6, .25, 25	168, .40		.6356
		168, 5, 80, -40	33, 6, .25, 25			.6080
		168, 5, 80, -40	33, 6, .25, 25		168, .40	.6366
		168, 5, 80, -40				.5998
		168, 10, 80, -40	33, 6, .25, 25	168, .20		.3226
		168, 10, 80, -40	33, 6, .25, 25			.6083
		168, 10, 80, -40	33, 6, .25, 25		168, .20	.6228
		168, 10, 80, -40				.6000
		168, 20, 80, -40	33, 6, .25, 25	168, .10		.6155
		168, 20, 80, -40	33, 6, .25, 25			.6083
		168, 20, 80, -40	33, 6, .25, 25		168, .10	.6156
		168, 20, 80, -40				.6000
		64, 15, 80, -40		64, .133		.6037
	64, 80, .05 64, -40, .05	64, 15, 80, -40		64, .233		.6079
	1, 25, 100					.0427
	1, 25, 17.07					.0076
		64, 5, 80, -40	33, 6, .25, 25	64, .40		.5904
		64, 5, 80, -40	33, 6, .25, 25			.5786
		64, 5, 80, -40		64, .40		.5818
		64, 5, 80, -40				.5697
		64, 10, 80, -40	33, 6, .25, 25	64, .20		.6124
		64, 10, 80, -40	33, 6, .25, 25			.6068
		64, 10, 80, -40		64, .20		.6042
		64, 10, 80, -40				.5985
		64, 20, 80, -40	33, 6, .25, 25	64, .10		.6111
		64, 20, 80, -40	33, 6, .25, 25			.6082
		64, 20, 80, -40		64, .10		.6029
		64, 20, 80, -40				.6000

TABLE 2.4 Hughes Internal Data (Cont)

Reference	Constant Temp Cyc, Temp, Time	Cycled Temp Cyc, Temp Rate, Hi, Lo	Vibration Cyc, g's, Time Temp	Constant Power Cyc, Time	Cycled Power Cyc, Time	Test Strength
F-15						
3 tests – card level		168, 5, 115, -55				.6000
unit level		33, 5, 70, -40			33, .367	.4664
equip. level		30, 5, 71, -55			30, .367	.4662

SECTION 3.0 – DESCRIPTION OF IMPORTANT MODEL VARIABLES

3.1 Role of Test Strength in the Screening and Debugging Optimization (SDO) Model

The idea in a sequence of screens is the successive removal of defects. For screens that do not damage good items the probability of "catching" a defect is generally not one. Thus if D_I defects are submitted to the first of $k \geq 1$ screens the number of defects caught by the first screen will be (say) $\bar{D}_1 \leq \bar{D}_I$. The number of defects entering the second screen (neglecting rework cycles to simplify the illustration) is the $D_I - \bar{D}_1$ and if the number caught by the second screen is $\bar{D}_2 \leq D_I - \bar{D}_1$ the number of defects entering the third screen is $D_I - \bar{D}_1 - \bar{D}_2$ and so on.

Test strength, the probability that a given defect will be caught by the k^{th} screen, is called TS_k and TS_k assists in providing a mathematical model for the screening process. The actual number of defects removed solely by the k^{th} screen is a random variable whose domain is the set of positive integers

$$0, \ldots, D_I - \sum_{i=1}^{k-1} \bar{D}_i$$

where of course $\bar{D}_i$, the number removed at the i^{th} screen, $1 \leq i \leq k$ is also a random variable. To carry the analysis throughout the process on the basis of random variables is quite complicated so we deal with expected values. Thus, if D_I defects enter screen one, two quantities are of interest

i) the expected number of defects entering the second screen:

   $D_I - TS_1 D_I = (1 - TS_1)\, D_I$. That is, this quantity is the expected number of defects not caught.

ii) the expected number of defects removed by the first screen:

   $(TS_1)\, D_I$.

The expected number of defects removed by the second screen is $(TS_2) \times (1 - TS_1)D_I$ and hence the expected number of defects entering the third screen is $(1 - TS_1)\,(1 - TS_2)\, D_I$. The expected number of defects removed by the third screen is $TS_3\,(1 - TS_1)\,(1 - TS_2)\, D_I$ so that the expected number of defects entering the fourth screen is $(1 - TS_1)\,(1 - TS_2)\,(1 - TS_3)\, D_I$. In general then the expected number of defects entering the k^{th} successive screen is

$$\prod_{i=1}^{k-1} (1 - TS_i)\, D_I$$

and if the sequence is stopped at, but including, the k^{th} screen the final defects remaining

$$D_F = \prod_{i=1}^{k} (1 - TS_i)\, D_I.$$

In the next section we obtain interval estimates of the random variable D_I.

3.2 Interval Estimates for the Number of Defects Remaining, D_F - Monitoring/Controlling the Screening Process.

As noted in the previous section the entire process of starting with D_I initial defects and removing defects by a sequence of screens until there are only D_F defects left after the last screen is a random process. The SDO model works, necessarily, with expected values; to do otherwise would result in enormous costs.

However, the fact remains D_I, D_F are random unknown quantities and the model works with the expected values of D_I and D_F. Now suppose there are $k \geq 1$ screens in the entire process with TS_i, $i=1, \ldots, k$ the test strength of the i^{th} screen. The only observable (random) quantities are the number of defects caught at each screen, $\overline{D}_i$, where $\overline{D}_i$ represents the number caught at the i^{th} screen. It would be of value to have confidence interval estimates of D_I and D_F; neither of which is observable. D_F is particularly important because it is the number of defects remaining in the "system" after the last (k^{th}) screen is completed. We note again that

$$D_F = D_I - \sum_{i=1}^{k} \overline{D}_i$$

That is, the number of defects remaining after the last (k^{th}) screen is the initial number present minus the total of those removed, caught or detected.

It is fairly easy to show that the probability distribution of $\overline{D}_k$, the number of defects caught by the last screen is binomial with parameters D_I and

$$\prod_{i=1}^{k} (\overline{TS}_i)$$

where

$$\overline{TS}_i = 1 - TS_i, \text{ i.e.,}$$

$$P(\overline{D}_k = X) = \binom{D_I}{X} \left[\prod_{i=1}^{k} \overline{TS}_i \right]^X \left[1 - \prod_{i=1}^{k} \overline{TS}_i \right]^{D_I - X}$$

In this expression there are three quantities of importance: D_I (not observable),

$$\prod_{i=1}^{k} \overline{TS}_i$$

(computable from the test strength equations) and X the observable number of defects actually caught at the last (k^{th}) screen. Hence the known quantity

$$\prod_{i=1}^{k} \overline{TS}_i$$

and the observable quantity X can be used for inferences on D_I.

Once having obtained inferences on D_I we can obtain inferences on

$$D_F = D_I - \sum_{i=1}^{k} \bar{D}_i$$

since

$$\sum_{i=1}^{k} \bar{D}_i$$

is observable (it is the total defects detected). Of course only upper confidence bounds on D_F are of interest. If not all the parts are tested, the value of D_F must be adjusted according to what fraction is tested.

Example

Suppose k = 3 screens with test strengths $TS_1 = 0.50$, $TS_2 = 0.50$, $TS_3 = 0.20$. Suppose also that at screen one 6 defects are caught, at screen two 2 defects are caught and at screen three 1 defect is caught. Then $\bar{D}_1 = 6$, $\bar{D}_2 = 2$, $\bar{D}_3 = 1$. Thus

$$\sum_{i=1}^{3} \bar{D}_i = 9 \text{ and } \prod_{i=1}^{3} \overline{TS}_i = (0.50)(0.50)(0.80) = 0.20, \; \overline{TS}_i = (1 - TS_i).$$

Hence,

$$P(\bar{D}_3 = X) = \binom{D_I}{X} (0.20)^X (0.80)^{D_I - X}.$$

But we have observed X = 1. Proceeding to tables of the binomial probability distribution with "p" = 0.20 we find

$$P(X \leq 1 \mid D_I = \text{"n"} = 20) = 0.07$$

Hence the confidence is 0.93 that $9 \leq D_I \leq 19$, and hence the confidence is 0.93 that

$$D_I - \sum_{i=1}^{3} \bar{D}_i = D_F$$

is less than or equal to 19-9 = 10.

These interval estimates can be prepared AFTER EACH SUCCESSIVE SCREEN to monitor/control the evolution of the entire process. That is, the interval estimate of D_F at the m^{th} stage can be compared with the expected results (at the m^{th} stage):

$$D_F^m = E(D_I) \left[\prod_{i=1}^{m} \right] \overline{TS}_i$$

where $\langle D_I \rangle$ is expected value of D_I used in the SDO model. Discrepancies between observed and expected results must be resolved between two items: was the initial $\langle D_I \rangle$ incorrect or is one (or more) of the TS_i's incorrect. In any case the observed D_F^m's can be projected ahead to see what D_F might finally be by using the $\overline{TS}_{m+1}$, $\overline{TS}_{m+2}$, ..., $\overline{TS}_k$ to predict the final D_F^k from the observed results up to the m^{th} test and the expected results from the $(M+1)^{st}$ stage to the k^{th} stage.

Example

We continue with the previous example and suppose there is one more last test to be run with $TS_4 = 0.15$ and after all four tests we had hoped to have $D_F \leq 8$. We already have any upper confidence limit of 10 on D_F^3 and $D_F = D_F^4 = \overline{TS}_4\ (D_F^3) = (0.85)\ 10 = 8.5$ which is an upper 0.93 confidence limit on D_F and the achievement of $D_F \leq 8$ appears to be entirely feasible.

3.3 Role of Part Level Screens

The SDO model developed as a result of this study does not include, explicitly, a part level screen. This was done for two reasons. As will be described in Section 5.0 the initial number of defects, D_I, is an entry variable in the model. D_I is a function of the number of parts, say N, in the system (a quantity known to a careful reliability engineer), and the fraction defective, say p, of the incoming parts. Thus, $D_I = N_pS$ (where S is the number of systems) and p is a function of quality level (e.g., commercial, B-level) of part purchased. In order to keep the CPU time and core requirements of the SDO model within bounds it was felt that the user can easily price the various quality grades and compute D_I as a function of quality (p) and price then for each D_I run the SDO model to see, as D_I varies, which is the most economical part quality level to purchase. For example, suppose the final tolerable defects $D_F = 20$ and that "to go" from $D_I = 500$ to $D_F = 20$ costs \$100,000 worth of screens and that to go from $D_I = 250$ to $D_F = 20$ costs \$63,000 worth of screens. Now suppose N = 25,000 and p = 0.01 for B-level and p = 0.02 for commercial parts. If the incremental cost of the B-level parts is less than \$37,000 it is cheaper to start with B-level parts.

The second reason part level screens have been omitted from the model is the "exploding" effect of part level defects when the parts are assembled on cards. What this means is that part screening, while probably relatively inexpensive, must have a tremendously high (near one) TS to prevent defective cards. For example, suppose a large (the parts are used on many programs not just "yours") part population which has p = 0.02 and that the cards will have 150 parts/card. Then the expected number of defects per card is 0.02 x 150 = 3 and since it takes only one or more bad parts to make a bad card it is clear, using the Poisson approximation, the fraction of bad cards (a card with one or more defects) is on the order of 0.95. Thus to keep the fraction bad cards low the parts must be screened with high TS. For example, suppose TS (at the part level) is so high that p = 0.02 can be reduced to 0.001, a 20-1 reduction. Then the expected number of defects/card is 0.001 x 150 = 0.15 and the fraction of bad cards is on the order of 0.14 - a reduction by a factor of only 7-1.

A more accurate analysis requires some notation and a small amount of probability calculus. Let the following definitions be made:

N = number of parts in lot

M = number of cards to be made

m = number of parts per card

($mM \leq N$)

p = fraction defective of the lot

X_i = number of defective parts on the i^{th} card $i = 1, \ldots, M$

Then Np is the total number of defective parts in the lot, the X_i are random variables and

$$P(X_1 = x_1, \ldots, X_M = x_M) = \left[\frac{\binom{Np}{x_1}\binom{N-Np}{m-x_1}}{\binom{N}{m}}\right]\left[\frac{\binom{Np-x_1}{x_2}\binom{N-m-(Np-x_1)}{m-x_2}}{\binom{N-m}{m}}\right] X \ldots$$

$$\ldots X \left[\frac{\binom{Np - \sum_{i=1}^{M-1} x_i}{x_M}\binom{N-(M-1)m-(Np - \sum_{i=1}^{M-1} x_i)}{m-x_M}}{\binom{N-(M-1)m}{m}}\right]$$

where

$$\binom{x}{y} = \frac{x!}{y!(x-y!)} \quad x \geq y$$

The card fraction defective is then (since it is clear that it is immaterial which $1 \leq i \leq M$ of the M cards is defective and zero defective cards contributes nothing to the sum, i.e., $0/M = 0$).

$$\sum_{i=1}^{M} \left(\frac{i}{M}\right)\binom{M}{i} P(X_1 = 0, \ldots, X_{M-i} = 0, X_{M-i+1} \geq 1, \ldots, X_M \geq 1)$$

where

$$P(X_1 = 0, \ldots, X_{M-i} = 0, X_{M-i+1} \geq 1, \ldots, X_M \geq 1)$$

$$= \sum_{\substack{X_{M-i+1}, \ldots, X_M \geq 1 \\ X_1, \ldots, X_{M-i} = 0 \\ \sum x_i \leq mN}} P(X_1 = x_1, \ldots, X_M = x_M)$$

The following examples give a very few results since the computations involved can quickly out-distance even a large high-speed digital computer.

Example 1

$N = 1000$, $p = 0.01$, $m = 50$, $M = 10$: the card fraction defective is about 0.40.

Example 2

$N = 5000$, $p = 0.01$, $m = 100$, $M = 25$: the card fraction defective is about 0.63.

3.4 Determination of Test Strength (TS)

The ability of particular screen to detect incipient/latent defects will be called test strength (TS) and is represented formally as a probability

TS = the probability that a given screen, including the test set-up, will detect an incipient/latent defect.

The portion of TS relating solely to the ability of the screen to degrade the defect to a detectable level is called screening strength, SS, and the portion relating to the ability of the test equipment/set-up to detect the defect once it has been degraded to a detectable level is called P_d.

Thus, $TS = SS \times P_d$.

Ordinarily, TS is not computable or estimable. For any given screen (with test set-up) TS could be estimated by

$$TS = \frac{\text{number of defects detected after screen}}{\text{number of defects entering screen}}$$

Unfortunately, the denominator of this fraction is usually unknown. It would be possible to estimate TS by placing a known number of bad items on the screen and observing the results but we could uncover no such experiments. Many experiments involve comparing screens for their relative TSs. Thus, if 100 cards are put on each of five different screens (say S_1, S_2, ..., S_5) then assuming the number of defects entering the five screens are equal, the screens can be ranked by the number of defects discovered by the screens and the screens with the largest fallout will be best. However, these sorts of results do not permit actual computation of TS_i, $i = 1, \ldots, 5$ but only permit computation of the ratios

$$\frac{TS_j}{TS_k} \cdot j = 1, \ldots, 5 \quad k = 1, \ldots, 5, \; j \neq k.$$

Two approaches to computing TS are available and both have been used in this study. First, from the results of the questionnaire, several respondents felt they had enough experience with incoming defect rates so that we could compute TS for these responses. This occurred about fifteen times. The second approach is to build mathematical functions, derived from the physics of the screening environment, which yield TS (or SS). This has been done by the Hughes Aircraft Company in their Cost Reduction by Early Decision Information Techniques (Ref 42) program (Report No. TIC 20-42-732-R (P73-218)). In that report, equations are given for SS for vibration, constant temperature and temperature cycling screens. These equations were used to compute the SS used in the cost models. Before giving these equations we note that such equations are not available for power applied screens and this power-applied case is treated first.

Probability of detection, P_d, presents a different problem: it is highly dependent on the individual test setups. We have not found nor have we developed quantitative models for computing P_d. However, the factors to be included in P_d are: possible failure modes, functions performed, functions tested, test equipment available, test equipment quality and calibration, instrumentation setup and data recording.

3.4.1 TS for Power Continuously Applied Screens

Seven respondents to the questionnaires had conducted continuously applied (rated) power tests with all other conditions at ambient. We were able also to compute the TS_i's for these seven tests and of course the seven test times, t_i, were also available. The usual procedure is to fit (to the data) various linear or linear-izable functions by least squares and select the one which is best fit. In the present case, TS must satisfy $0 \leq TS \leq 1$ so we first selected a function of t (time of continuously applied rated power) such that TS = 0 at t = 0 and TS = 1 at $t = \infty$. Such a function is

$$TS = g(t) = \frac{bt}{a + bt}, \quad a, b, t > 0,$$

$$= 0 \text{ elsewhere.}$$

Obviously,

$$TS = g(t) = \frac{t}{\frac{a}{b} + t}$$

so that TS depends only on the ratio a/b = c.

$$TS = g(t) = \frac{t}{t + c} \qquad (1)$$

A description of the results for obtaining the constant c is contained in Section 4.1. No data was available for the case when the power applied was other than rated.

3.4.2 TS for Cycled (ON/OFF) Rated Power

The continuously applied rated power case is just a special case of this present case when the number of cycles, say N_c, is one. Now suppose $N_c > 1$, then TS, the probability of detection is just one minus the probability of non-detection in N_c cycles. That is,

$$TS = 1 - \left(1 - \frac{t}{t + c}\right)^{N_c} \quad (2)$$

where

N_c = number of cycles

t = length of a cycle in hours

This reduces to equation (1) when $N_c = 1$.

At first glance it appears that equation (2) "neglects" the screening effect due solely to the act of "turning" the power off and on. This is not quite true as can be test seen by an example. Suppose $N_c = 18$ and $t = 4$. Then from equation (2), using $c = 886.62$,

$$TS = 1 - \left(\frac{886.62}{890.62}\right)^{18} = 0.078.$$

If however we choose to neglect the cycling and just assume 4 x 18 total hours of screening and apply equation (1)

$$TS = \frac{72}{72 + 886.62} = \frac{72}{958.62} = 0.075$$

which is less (test strength) than 0.078. It is trivial to show that equation (2) always gives greater TS than equation (1) with $t' = N_c t$ where t is the length of a cycle.

Thus, the effect of the on/off portion is included. Equation (2) may be generalized to the case where each of the N_c cycles has a differing time t_i, $i = 1, \ldots, N_c$:

$$TS = 1 - \prod_{i=1}^{N_c} \left(\frac{c}{c + t_i}\right)$$

3.5 Determination of Initial (D_I) and Final (D_F) Defects

To use the SDC model for minimizing cost the user must enter, among other parametric values, the initial (D_I) and final (D_F) number of defects desired.

D_I should be based on the total parts count for the system, the number of systems, and the expected part fraction defective. This latter number will ordinarily be based on the quality level of parts purchased for each of the major part types. For example suppose a system is composed of mil std parts (B and C level quality grades) as well as non-standard parts, then D_I is calculated as follows:

Part Type	Quantity	Quality Grade	% Defective
Resistors	1,000	C level	3
ICs	10,000	B level	1
Non-standard (various)	3,000	non-mil std	5

$D_I = 1,000(0.03) + 10,000\ (0.01) + 3,000\ (0.05) = 280$

The computer program defaults to 1% in the absence of user specification.

D_F is determined by using the mature MTBF θ_M (e.g., obtained from a MIL-HDBK-217B prediction), θ_F the required MTBF before field delivery, and a relatively long period of field operation, say t, in the following equation

$$D_F = \left| \frac{t}{\theta_F} - \frac{t}{\theta_M} \right| (TS)^{-1}$$

The left hand term in the bracket is the expected number of failures in t (field) hours when the MTBF IS θ_F, the at-delivery MTBF. The right hand term is the expected number of random failures in t (field) hours. Thus the difference is the expected number of engineering errors, manufacturing quality and unreliability failures removed during t (field) hours. When this difference is divided by the test strength for t (field) hours, D_F is obtained. That is, the equation

$$D_F \times TS = \left[\frac{t}{\theta_F} - \frac{t}{\theta_M} \right] \text{ is solved for } D_F.$$

The SDO model has this equation in it with t = 26.280 hrs (3 years operation) and the computation of TS is performed by the program.

Example

Suppose θ_F = 300 hours, θ_M = 420 hours, and t = 10,000 hours with no temperature or vibration excursion expected during field operations. Then, (see Section 4.1.2).

$$TS = \frac{t}{t+c} = \frac{10,000}{10,000 + 4,066} = 0.71$$

$$t/\theta_F = \frac{10,000}{300} = 33.3;\ t/\theta_M = \frac{10,000}{420} \doteq 23.8$$

and

$$D_F = \frac{[33.3 - 23.80]}{0.71} = 13.4 \cong 13.$$

SECTION 4.0 -- DATA ANALYSIS FOR MODEL PARAMETERS

4.1 Computation of Test Strength for Power Applied

4.1.1 Test Strength (TS) for Card/Unit Level:

The BMD07R, non-linear least squares computer program (described in the Appendix) was used to find the parameter, c, in the functional equation: $TS = t/(t + c)$. Using the seven data points shown in Table 4.1 (which were obtained from the questionnaire), an initial estimate of c = 1000.0 allowed the iteration scheme to converge in a few steps to c = 886.62.

These survey points were also used to find a and c in $TS = (t/(t + c))^a$ and a and b in $TS = 1.0 - \exp\left[-(t/a)^b\right]$. However, using these functional equations did not improve upon the performance of $TS = t/(t+c)$ with respect to low estimating error.

The QKPLOT graphics subroutine (described in the appendix) was then used to plot Test Strength (TS) versus time (t) using the equation $TS = 1.0 - [886.62/(t + 886.62)]^{N_c}$. Three curves were produced where $N_c = 1$, $N_c = 5$, and $N_c = 10$ (see Figure 4.1) as a means of illustrating the improvement in TS as N_c, the number of cycles gets large.

Another illustration worth looking at is, for fixed total time T, the improvement in cycled power versus continuous power applied.

Suppose the total time of power applied T = 200 hours. We consider

Case 1 200 hours of continously applied power

$$TS = \frac{t}{t + c} = \frac{200}{200 + 886.62} = 0.184$$

Case 2 2 cycles of t = 100 hours each

$$TS = 1 - \left[\frac{886.62}{886.62 + 100}\right]^2 = 0.192$$

Case 3 4 cycles of t = 50 hours each

$$TS = 1 - \left[\frac{886.62}{886.62 + 50}\right]^4 = 0.198$$

Case 4 8 cycles of t = 25 hours each

$$TS = 1-\left[\frac{886.62}{886.62 + 25}\right]^8 = 0.200$$

TABLE 4.1. Questionnaire Data Points

	Time (t)	Test Strength (TS)
1	168	.09257
2	168	.02900
3	100	.05696
4	96	.05479
5	96	.50000
6	48	.02805
7	17.07	.01013

Case 5   16 cycles of t = 12.5 hours each

$$TS = 1 - \left[\frac{886.62}{886.62 + 12.5}\right]^{16} = 0.201$$

While obviously more costly, the large cycles have slightly better TS. Clearly the upper limit of TS obtainable by infinitesimal lengths t of an infinite number of cycles is, for power applied for total time T,

$$1 - e^{-T/886.62}.$$

Thus, since the worst case is $N_c = 1$ which has

$$TS = \frac{T}{T + 886.62},$$

then the difference

$$(1 - e^{-T/886.62}) - \left(\frac{T}{T + 886.62}\right)$$

represents the total possible improvement in TS for fixed total time T.

In the preceding example this difference is on the order of 0.201 - 0.184 = 0.017 which hardly seems worth the trouble of using $N_c > 1$.

4.1.2 Test Strength (TS) for Equipment/System Level:

The BMD07R computer program (described in the appendix) was used again to find the parameter, c, in the functional equation TS = t/(t+c). TS (test strength) was computed from the data points using the formula $TS = 1.0 - (\theta_{Initial}/\theta_{Final})$.

Eighteen, and finally, sixteen values of time (t), MTBF initial and final (θ_I, θ_F) from the internal data base (see Table 4.2) were used, along with an initial estimate of c = 5000.0. This allowed the iteration scheme to converge in eight steps to c = 4084.8 and c = 4066.5, respectively. The SDO model uses c' = 3049.875 = (0.75) (4066.5) in order to "factor out" the probability of detection, P_d. That is, the SDO model uses $TS = t/(t + c'/P_d)$ because it separates SS and P_d.

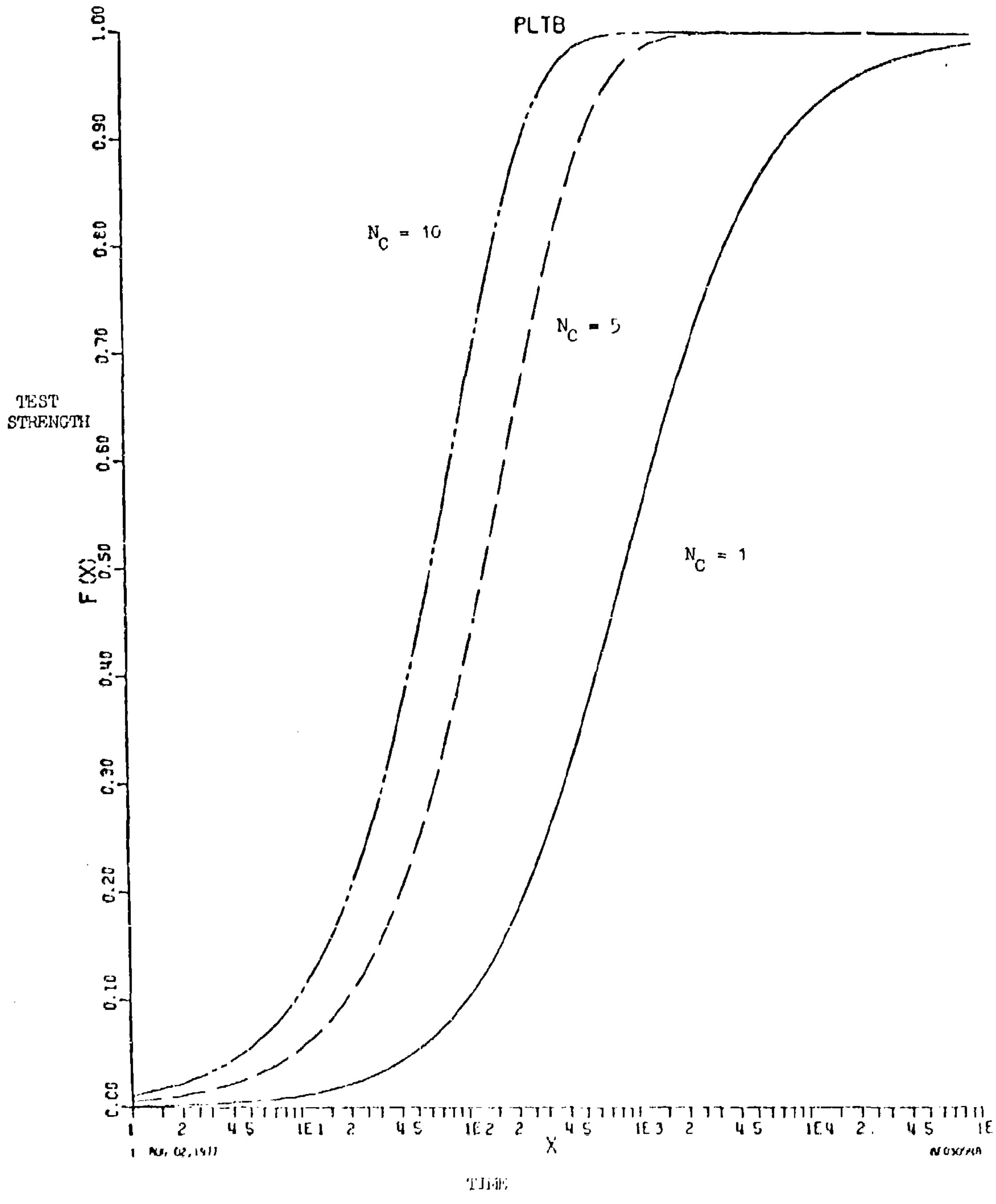


FIGURE 4.1 POWER TEST STRENGTH

TABLE 4.2. Internal Data Points

	Time	$\theta_{Initial}$	θ_{Final}	Test Strength
1	4000	150	300	.5000
2	5000	50	100	.5000
3	1689	42	98	.5714
4	1690	92	216	.5741
5	4200	14	148	.9054
6	15000	10	29	.6552
7	4502	.6	17	.9647
8	16491	83	192	.5417
9	5986	134	456	.7061
10	14006	283	581	.5129
11	10339	182	233	.2189
12	4312	17	54	.6852
13	15519	231	251	.0797
14	5537	8	17	.5294
15	12100	6	22	.7273
16	6100	71	126	.4365

The Reliability Growth Study (ref. 47) provided eighty-one triples of time t, P_1 (Duane logarithmic growth rate) and P_2 (Duane intercept parameter) for in-house ground (thirty-one points) and in-house airborne (fifty points) systems. Sixty-three of these points were used in a subsequent analysis (see Section 4.3) with the IBM model and are shown in Table 4.3. Using this data, the test strengths were computed from the above formula and $\theta_{Initial}$ and θ_{Final} were computed using:

$$\theta_I = P2 * \Gamma\left[(1.0/P1) + 1.0\right]$$

and

$$\theta_F = \left[P2^{P1} * t^{(1.0 - P1)}\right]/P1$$

Using initial estimates of the parameter c, the iteration converged to c = 260.06 for the airborne data; c = 916.31 for the ground data, and c = 337.10 for the ground and airborne data combined.

In order to see if test strength could be written as a function of several variables, the Multiple Linear Regression (MLRG) subroutine (described in the appendix) was used. With test strength (TS) as the dependent variable, various combinations of time, parts count, and environmental conditions were tried as independent variables. In all cases R^2, the coefficient of multiple determination, was very small (see Table 4.4).

The value c = 4066.5 was used because the internal data base provided the best fit.

TABLE 4.3. Reliability Growth Data

	Time	$\theta_{Initial}$	θ_{Final}	TS	Y'
1	3038	330.63	1781.5	.81441	$.77819 \times 10^{2}$
2	3822	452.02	2030.5	.77739	$.22781 \times 10^{-9}$
3	6369	44.516	362.86	.87732	$.28907 \times 10^{1}$
4	3822	131.49	254.52	.48339	$.64664 \times 10^{-34}$
5	1122	30.115	35.344	.14794	$.45780 \times 10^{-4}$
6	2700	.099636	62.614	.99841	$.68262 \times 10^{-1}$
7	3200	.41363	67.855	.99390	$.37012 \times 10^{-2}$
8	3700	3.6481	142.88	.97447	$.88842 \times 10^{-5}$
9	3700	1.0919	308.20	.99646	$.41420 \times 10^{-5}$
10	2500	77.812	204.56	.61961	$.27362 \times 10^{-1}$
11	2193	23.643	228.75	.89664	$.58012 \times 10^{-6}$
12	2248	43.723	81.398	.46285	$.22290 \times 10^{1}$
13	3415	.60827	13.321	.95434	$.12416 \times 10^{3}$
14	4659	430.02	1150.4	.62619	$.27249 \times 10^{-7}$
15	6144	196.60	337.75	.41793	$.15031 \times 10^{2}$
16	4467	8.0679	172.94	.95335	$.22948 \times 10^{-5}$
17	2043	29.593	336.10	.91195	$.10984 \times 10^{-5}$
18	2792	234.62	360.44	.34908	$.85282 \times 10^{-5}$
19	1540	14.205	39.810	.64317	$.12821 \times 10^{-7}$
20	1726	3.5269	726.54	.99515	$.83703 \times 10^{-6}$
21	2261	3.0704	215.75	.98577	.38257
22	3105	766.40	3595.0	.78681	$.12800 \times 10^{1}$
23	3415	4.7866	74.381	.93565	$.74311 \times 10^{1}$
24	4536	3.7041	123.07	.96990	$.16717 \times 10^{1}$
25	4536	310.54	548.30	.43364	$.34030 \times 10^{1}$
26	2076	69.100	202.04	.65799	$.13173 \times 10^{-30}$
27	5085	29.501	128.74	.77085	$.33722 \times 10^{2}$
28	1122	24.439	36.220	.32525	$.30769 \times 10^{-15}$
29	1400	22.256	61.352	.63724	$.18048 \times 10^{1}$
30	400	22.892	75.951	.69859	$.58302 \times 10^{1}$
31	1200	7.3325	106.40	.93108	$.18408 \times 10^{-2}$
32	4988	4.2615	44.205	.90360	$.48216 \times 10^{3}$

TABLE 4.3. Reliability Growth Data (Continued)

	Time	$\theta_{Initial}$	θ_{Final}	TS	Y'
33	1000	.92606	47.765	.98061	$.13708 \times 10^{-1}$
34	2176	.027881	11.465	.99757	.11321
35	400	2.4662	24.715	.90022	$.15516 \times 10^{1}$
36	1300	1.0681	65.495	.98369	$.92072 \times 10^{-2}$
37	4996	36.735	95.991	.61730	$.21104 \times 10^{1}$
38	1200	41.069	167.65	.75504	.12586
39	536	96.734	116.72	.17123	$.86898 \times 10^{-1}$
40	500	21.399	88.647	.75860	.15739
41	760	8.8171	183.88	.95205	.14099
42	1400	31.520	61.006	.48333	.11316
43	800	29.775	74.712	.60148	.12527
44	760	32.189	213.28	.84908	.12449
45	782	39.047	202.26	.80694	$.17877 \times 10^{-6}$
46	767	17.226	125.43	.86267	$.57691 \times 10^{-1}$
47	760	25.414	125.13	.79690	$.22788 \times 10^{1}$
48	782	33.681	301.72	.88837	.50858
49	760	7.0105	82.785	.91532	.26110
50	782	9.4446	106.30	.91115	$.22573 \times 10^{-2}$
51	767	5.4092	108.96	.95036	.25400
52	2500	1.5325	73.877	.97926	$.48286 \times 10^{-15}$
53	798	.25120	14.433	.98260	$.16778 \times 10^{-1}$
54	1097	.60820	14.040	.95668	.40146
55	399	.33733	11.201	.96988	$.13968 \times 10^{2}$
56	1192	.12900	5.5837	.97690	$.37987 \times 10^{-1}$
57	2500	.84153	11.323	.92568	$.14334 \times 10^{-11}$
58	760	1.12714	62.248	.97958	.32929
59	500	6.5611	41.867	.84329	$.28217 \times 10^{1}$
60	767	6.4641	85.624	.92451	$.56011 \times 10^{-1}$
61	782	6.0595	89.320	.93216	$.32853 \times 10^{-1}$
62	766	5.9670	40.514	.85272	.21182
63	549	6.9464	16.115	.56896	.16692

Note: Numbers 1-28 represent the ground data.
Numbers 29-63 represent the airborne data.

TABLE 4.4. Test Strength as a Function of Several Variables

Independent Variables	R^2 = Coefficient of Multiple Determination
Environmental Conditions, Parts Count, and Time	1.72927×10^{-1}
Parts Count and Time	9.75238×10^{-2}
Environmental Conditions and Time	1.58463×10^{-1}
Time	6.47496×10^{-2}

4.2 Test Strength for Constant Temperature, Temperature Cycling, Vibration, and Combined Screens

The equations utilized for these screens were developed using Arrhenius relations and were taken from the Hughes Aircraft Company CREDIT report (ref 42). Test strength for k combined screens is defined as $TS = 1 - \prod_{i=1}^{k} (1-TS_i)$. That is, total test strength is the probability the defect is detected on at least one of the screens which is one minus the probability it is not detected on any of the screens.

Five types of screens are provided in the model: the two power screens previously discussed and temperature cycling, constant temperature and vibration. If a particular screen is not used its' TS defaults to 0.

$$TS1 \text{ (constant temp)} = \left[0.6 \times P_d \left[1-e^{-N \times t_T \times 2.63 \times 10^{-5} \times e^{0.0122(T_a+273)}}\right]\right]$$

$$TS2 \text{ (cycled temp)} = \left[0.8 \times P_d \left[1-e^{-N \times \frac{dT_i}{d_t} \times 11.835 \times 10^{-5} \times e^{.0122(T_{dt}+273)}}\right]\right]$$

$$TS3 \text{ (vibration)} = \left[0.2 \times P_d \left[1-e^{-N \times g \times t_v \times 7.69 \times 10^{-5} \times e^{.0122(T_v+273)}}\right]\right]$$

where N = number of cycles

t_T = time of temperature exposure (hours)

T_a = actual temperature (^oC)

$\frac{dT_i}{dt}$ = rate of temperature change (^oC/min)

T_{dt} = $(|\text{hi temp} - 25| + |\text{lo temp} - 25| + 50)/2$ (^oC)

where g = vibration (g's) (sinusoidal at nonresonant frequency)

t_v = length of vibration (hours)

T_v = |temp at vibration −25| + 25 (°C)

The constants used are derived parameter values for cards containing miscellaneous parts, with the exception of 0.75 which is the default of P_d used in the definition of test strength. No "model" was available, anywhere, for P_d. The value 0.75 is the best number available based on Hughes internal experience.

4.3 Conversion of MTBF (θ) to Defects

Several methods were tried in order to convert MTBF to defects. The recommended method is described in Section 3.5. In this section we describe other methods which were not successful. The multiple linear regression (MLRG) subroutine (described in the appendix) was used to write the dependent variable Y = OMR/Part Count as a function of the independent variables, MTBF final and MTBF predicted. In each case R^2, the coefficient of multiple determination, was very small. Eighteen values of the internal data were used, producing the results with Y as defined above:

Independent Variable	R^2
θ Final, θ_F	5.98614×10^{-2}
θ Predicted, θ_P	7.18709×10^{-2}

CURFIT, a least squares curve fit program (described in the appendix), was implemented using Y = OMR/Part Count as the dependent variable versus the independent variables of θ_{Final}, and $\theta_{Predicted}$. Also, Y = OMR was used as a dependent variable versus the same independent variables as above. The data points used came from the internal data values. The results in Table 4.5 show that the coefficient of multiple determination was very small for all equation types.

Data values from the "Reliability Growth Study" (ref. 47) IBM model, "In-house" ground and airborne systems were combined with corresponding ones from the Duane model (refer to Table 4.3) to produce sixty-three points that were used in the CURFIT program. The dependent variable $Y' = K_1 e^{-K_2 t} = P2e^{-P3t}$ (P2 and P3 are the computer codes used in ref. 47) and the independent variable θ_F was computed from the Duane model. The IBM model gives: Cumulative number of correctable failures at remaining time $t = K_1 e^{-K_2 t}$. Obviously (when t = 0) K_1 is the initial number of defects present and K_2 is a "removal rate." Thus at program end (i.e., at delivery time) t_F, $Y' = K_1 e^{-K_2 t_F}$ is D_F.

Again, the coefficient of multiple determination was very small when it could be computed, as Table 4.6 shows that there was no fit possible for four of the six curve types.

The poor results caused us to abandon this approach to converting θ to defects. The approach adopted is given in Section 3.5.

TABLE 4.5. Conversion of MTBF to Defects Using Internal Data

Curve Type	Y = OMR versus θ_{Final}			Y = OMR versus $\theta_{Predicted}$		
	Index of Determination	A	B	Index of Determination	A	B
$Y = A+BX$	0.102556	256.142	-0.457676	$4.88187x10^{-3}$	190.131	$-6.21918x10^{-3}$
$Y = Ae^{BX}$	0.190088	160.936	$-3.33675x10^{-3}$	$1.55167x10^{-3}$	91.7242	$1.87763x10^{-5}$
$Y = AX^{B}$	0.263598	1126.6	-0.54605	$9.01423x10^{-3}$	186.17	-0.108185
$Y = A+B/X$	0.284264	65.565	6214.9	.108037	74.3455	42328.7
$Y = 1/(A+BX)$	0.085478	$1.25028x10^{-2}$	$4.7611x10^{-5}$	$1.29326x10^{-2}$	$2.16432x10^{-2}$	$-1.15342x10^{-6}$
$Y = X/(A+BX)$	0.140562	-0.497978	$2.95385x10^{-2}$	$3.96961x10^{-2}$	-2.92365	$2.76417x10^{-2}$

Curve Type	Y = OMR/Part Count versus θ_{Final}			Y = OMR/Part Count versus $\theta_{Predicted}$		
	Index of Determination	A	B	Index of Determination	A	B
$Y = A+BX$	$5.98638x10^{-2}$	$3.97853x10^{-2}$	$-9.51293x10^{-5}$	$7.18726x10^{-2}$	$1.62349x10^{-2}$	$6.49197x10^{-6}$
$Y = Ae^{BX}$	$9.34212x10^{-2}$	$1.06872x10^{-2}$	$-2.83562x10^{-3}$	$2.67243x10^{-2}$	$6.00225x10^{-3}$	$9.44587x10^{-5}$
$Y = AX^{B}$	0.167471	$7.45869x10^{-2}$	-0.527607	$5.38234x10^{-2}$	$8.91225x10^{-4}$	0.320457
$Y = A+B/X$	0.129448	$3.00551x10^{-3}$	1.14097	$8.52037x10^{-2}$	0.050509	-10.2266
$Y = 1/(A+BX)$	0.024747	257.687	.376589	$2.28171x10^{-2}$	346.902	$-2.25216x10^{-2}$
$Y = X/(A+BX)$	0.127914	-6983.29	449.607	$3.88004x10^{-4}$	4249.08	307.629

TABLE 4.6. Conversion of MTBF to Defects Using Reliability Growth Data

Curve Type	$Y' = K_1 e^{-K_2 t}$ versus θ_{Final}		
	Index of Determination	A	B
$Y = A+BX$	*	*	*
$Y = Ae^{BX}$	6.70122×10^{-5}	6.82998×10^{-4}	-2.19542×10^{-4}
$Y = AX^B$	1.35703×10^{-2}	0.321833	-1.32986
$Y = A+B/X$	*	*	*
$Y = 1/(A+BX)$	*	*	*
$Y = X/(A+BX)$	*	*	*

*No fit

4.4 Cost Data and Cost Equations

Cost data, as was previously mentioned, was obtained from the Hughes Aircraft Company manufacturing departments of the Fullerton and El Segundo sites.

It was decided, due to the instability of the dollar, to use man-hours as the basic unit of the cost data. This data was obtained by engineering estimates of a "typical" card, unit, equipment, and system man-hour usage of the five screening techniques addressed in this report, i.e., constant temperature, cycled temperature, vibration and, constant and cycled power.

Rework cost data was also given by engineering estimates of the cost involved as well as an estimate of number of defects caught by each rework cycle at "typical" card/unit and equipment/system levels.

The basic cost equation is of a linear nature where total cost = fixed cost + (variable cost x duration of test). The default used for fixed cost in the SDO model is zero due to the assumption that test equipment, etc., are already available to the user. The two defaults of the variable cost are derived from the cost data obtained at (d/unit and equipment/system levels respectively.

The cost equations derived for the following screens given for 1) card/unit levels, and 2) equip/system levels:*

Constant Temperature:

1. Test Cost = Fixed Cost + B1 x Test Time (man-hours)

2. Test Cost = Fixed Cost + B2 x Test Time (man-hours)

Cycled Temperature:

1. Test Cost = Fixed Cost + B1 x Difference in Temp Extremes x Rate of Temp Change x Number of Cycles

2. Test Cost = Fixed Cost + B2 x Difference in Temp Extremes x Rate of Temp Change x Number of Cycles

Vibration:

1. Test Cost = Fixed Cost + B1 x Duration of Vibration x Number of Cycles

2. Test Cost = Fixed Cost + B2 x Duration of Vibration x Number of Cycles

Constant Power:

1. Test Cost = Fixed Cost + B1 x Duration of Power Applied

2. Test Cost = Fixed Cost + B2 x Duration of Power Applied

*The constants B1 and B2 represent the average labor hours per hour of test in the default option for monitoring and data collection. The default values are 0.15 and 1.0 respectively and the fixed costs are zero.

Cycled Power:

1. Test Cost = Fixed Cost + B1 x Duration of Power Applied x Number of Cycles

2. Test Cost = Fixed Cost + B2 x Duration of Power Applied x Number of Cycles

Where time is given in hours and temperature is given in ^{0}C.

Rework costs are an integral part of the total cost considerations, rework's purpose being to correct those defects discovered by the screens. It is a cost that must be incurred as an alternative to discarding in that "new" inputs to a system may contain the same defects as a "rework" if not more. The following table represents the man-hours required to rework at card and higher assembly levels the defects discovered at card, unit, equipment, and system level as obtained from the survey and Hughes internal data.

TABLE 4.7. Man-hours Per Defect

Rework Location	Rework Man-Hours per Defect			
	Card	Unit	Equip	System
Card Level	.5	9.46	51.5	63.0
Higher Assy Level	.1	3.67	45.5	57.0

4.5 Determining Relationship of Number of Subcontractors and Percent Non-Standard Parts to Test Strength

To determine any relationship between Test Strength (TS) and number of subcontractors and percent non-standard parts, a requirement of the work statement, the computer program, CURFIT, described in the appendix, was implemented with data points from the internal data. $TS = 1.0 - (\theta_I/\theta_F)$ was used as the dependent variable versus the independent variables of number of subcontractors and percent non-standard parts. The results shown in Table 4.8 indicate that the index of determination was not very large in any of the curve fitting cases.

The BMD07R computer program (described in the appendix) was used to find the parameter, c, in the functional equation $TS = s/(s + c)$, where s = the number of subcontractors. Sixteen data points from the internal data were used with an initial estimate of c = 10.0 which allowed the iteration scheme to converge in eight steps to c = 3.8[illegible] This last analysis also showed no correlation between TS and subcontractors.

TABLE 4.8. Determining Relationship of Non-Standard Parts and Number of Subcontractors to Test Strength

Curve Type	TS versus Number of Subcontractors			TS versus Percent Non-Standard Parts		
	Index of Determination	A	B	Index of Determination	A	B
$Y = A+BX$	0.48996	0.467763	0.00878	2.34507×10^{-3}	0.535449	6.34608×10^{-4}
$Y = Ae^{BX}$	0.214789	0.421927	1.57241×10^{-2}	7.88787×10^{-4}	0.479895	9.95526×10^{-4}
$Y = AX^{B}$	0.342686	0.274205	0.341502	1.46446×10^{-4}	0.46517	2.14596×10^{-2}
$Y = A+B/X$	0.602609	0.854768	-1.24422	2.44974×10^{-3}	0.600488	-1.498
$Y = 1/(A+BX)$	6.90378×10^{-2}	3.01311	-4.16702×10^{-2}	2.85672×10^{-3}	3.00343	-8.85583×10^{-3}
$Y = X/(A+BX)$	0.390392	12.6619	-0.373962	7.9833×10^{-5}	-3.41908	2.60253

SECTION 5.0 – COST/STRENGTH MODELS

5.1 Manufacturing Process

From a product reliability point of view, the manufacturing-assembly-test process can be viewed as a "machine" for identifying and removing hardware defects that are induced through the use of defective parts (resistors, capacitors, ICs, etc.), poor designs and assembly errors. This machine can be effective by removing a large number of defects at a reasonable cost, or ineffective by removing only a small number of defects at a high cost and not meeting product reliability requirements imposed by the customer.

Figure 5.1 represents the various levels of assembly and test/rework stations at each level of a generalized manufacturing process. The process is cyclic in the sense that defects that are "caught" by a particular test may not be corrected (and removed from the process) but instead would go back into the process incurring additional test and rework costs. The symbols used to identify the process are defined below:

A_j	=	j^{th} assembly level
T_{jk}	=	k^{th} test of j^{th} assembly level
I_{jk}	=	Inspection/verification station for k^{th} test of j^{th} assembly level
PDEF	=	Quantity of part defects initially present
$ADEF_j$	=	Quantity of assembly defects initially present at the j^{th} level
X_{ijk}	=	Number of defects present at the start of the k^{th} test, j^{th} assembly level, during the i^{th} test/rework cycle.
Q_{ijk}	=	Probability of passing a defect from the k^{th} test to the $k + 1^{st}$ test, j^{th} assembly level during the i^{th} test/rework cycle.
P_{ijk}	=	$1 - Q_{ijk}$ = joint probability of raising a defect to a detectable level and detecting the defect with the test equipment employed at the k^{th} test, j^{th} assembly level, during the i^{th} test/rework cycle.
F_{ijk}	=	Fraction of the time a defect results in test/rework at the "card" assembly level (i.e., at j=1). The remaining portion of the time, $1 - F_{ijk}$, defects are tested/reworked at the j^{th} assembly level.
$R1_{ijk}$	=	Probability that a defect detected at the k^{th} test, j^{th} assembly level, during the i^{th} cycle is corrected (and removed from the process) during rework at the j^{th} card level.
$R2_{ijk}$	=	Probability that a defect detected at the k^{th} test, j^{th} assembly level, during the i^{th} cycle is corrected (and removed from the process) during rework at the j^{th} assembly level.

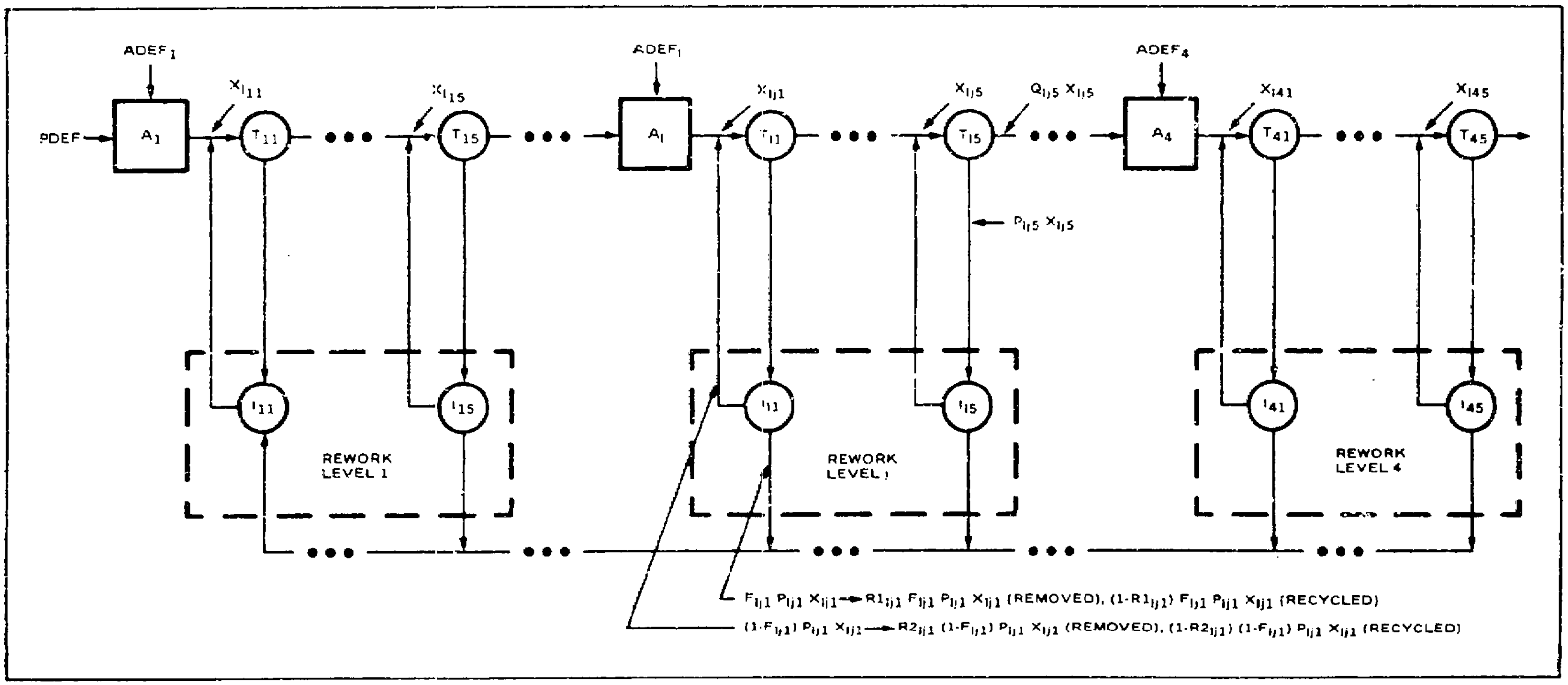


Figure 5.1. Generalized Manufacturing Assembly – Test Rework Process

Thus, at the first cycle (i=1) of test station T_{jk}, X_{1jk} defects (part and assembly defects that were not caught in the previous tests) are tested (stressed). Q_{1jk} X_{1jk} defects are not caught and are passed on to the next test and P_{1jk} X_{1jk} defects are detected and sent to the I_{jk} inspection station (for determination of defect type: card level or assembly level). F_{1jk} P_{1jk} X_{1jk} result in card level rework and $(1 - F_{1jk})$ P_{1jk} X_{1jk} result in assembly (j^{th}) level rework. Of the number of defects resulting in card level rework, $R1_{1jk}$ F_{1jk} P_{1jk} X_{1jk} will actually be corrected and removed from the process and $(1 - R1_{1jk})$ F_{1jk} P_{1jk} X_{1jk} will not be corrected. A similar breakdown of defects exists for assembly level rework. At the next cycle (i = 2), the number of defects entering the T_{jk} test station (i. e., X_{2jk}) is given by:

$$X_{2jk} = Q_{2jk} X_{2jk-1} + (1-R2_{1jk})(1-F_{1jk}) P_{1jk} X_{1jk} \qquad (1)$$

The first term on the right side of (1) represents defects passed by the previous test on the second cycle and the second term represents the assembly (j^{th} level) defects that were not removed from cycle 1.

The general equations representing the entire manufacturing process are given in Figure 5. 2. The equations are recursive with initial conditions as shown. A computer routine was developed to solve these equations and is provided as a subroutine (SCREEN) in the Screening and Debugging Optimization (SDO) model. The solutions $\{X_{njk}\}_{jk}$ provide the number defects present at the start of the n^{th} cycle for test stations $\{T_{jk}\}_{jk}$ so that for a given set of tests, the test strength TS is given by:

$$TS = 1 - \frac{D_F}{D_I} \qquad (2)$$

where:

$D_I = PDEF + \sum_{j=1}^{M} ADEF$; (incoming defects)

$D_F = \sum_{n=1}^{NCYC} Q_{nM\,N(M)} X_{nM\,N(M)}$ (outgoing defects - i. e., number remaining in the system)

PDEF = number of part defects

$ADEF_j$ = number of assembly defects introduced at the j^{th} assembly level

M = number of assembly levels

NCYC = maximum number of process cycles

$Q_{nM\,N(M)}$ = probability of passing a defect at final test (N(M)) of final level of assembly (M) during the n^{th} cycle.

$X_{nM\,N(M)}$ = number of defects present at the $N(M)^{th}$ test, M^{th} assembly level during the n^{th} cycle.

$$X_{i+1jK} = \begin{cases} P_{i+1\,j-1\,N(j-1)}\, X_{I+1\,j-1\,N(j-1)} + \left(1-P_{ijK}\right)\left(1-F_{ijK}\right)\left(1-R2_{ijK}\right) X_{ijK}, & \text{for } K=1,\ j>1 \\ P_{i+1\,jK-1}\, X_{i+1\,jK-1} + \left(1-P_{ijK}\right)\left(1-F_{ijK}\right)\left(1-R2_{ijK}\right) X_{ijK}, & \text{for } K>1,\ j\geq 1 \\ \sum_{n=1}^{M} \sum_{m=1}^{N(n)} \left(1-P_{inm}\right) F_{inm} \left(1-R1_{inm}\right) X_{inm}, & \text{for } K=1,\ J=1 \end{cases}$$

Initial Conditions

$$X_{111} = ADEF_1 + PDEF$$

$$X_{1j1} = P_{1j-1\,N(j-1)}\, X_{1j-1\,N(j-1)} + ADEF_j \quad \text{for } j>1$$

$$X_{1jK} = P_{1jK-1}\, X_{1jK-1} \quad \text{for } K>1$$

Figure 5.2. General Manufacturing Process Euqations

The corresponding cost function (TCOST) representing the total test and rework costs incurred during NCYC cycles is given by:

$$TCOST = \sum_{n=1}^{NCYC} \sum_{j=1}^{M} \sum_{k=1}^{N(j)} \left[CT_{jk} + CR_{njk} \left(1 - Q_{njk}\right) X_{njk} \right] \quad (3)$$

where:

CT_{jk} = test cost for conducting test T_{jk}

CR_{njk} = $CR1_{jk} F_{ijk} + CR2_{jk} (1 - F_{ijk})$

$CR1_{jk}$ = rework cost per cycle for defects identified for card level rework at the I_{jk} inspection station.

$CR2_{jk}$ = rework cost per cycle for defects identified for assembly level rework at the I_{jk} inspection station.

Other terms are as defined previously.

The manufacturing process represented by Figure 5.1 identifies the test stations (T_{jk}) at each level as separate events. The purpose of this separation is to compare test strengths and associated costs of individual screens as required for screen optimization (described in the next section). However, in actual practice, most testing at the same level of assembly is conducted in parallel. Thus, temperature cycling, vibration and power cycling may be used in a combined test (e.g., Test Level E of MIL-STD-781B).

It is generally felt that a combined test applies more stress on a unit than when the same tests are conducted separately because of the stress interactions. However, no information from the literature search or from internal data was found to support this contention, and therefore, the test strengths used do not reflect any stress interaction. The resulting effect of not including this additional stress of a combined test is a more conservative solution.

In addition, the manufacturing process assumes that defects which are not removed during a given rework cycle are (1) introduced back into the same test if classified to be an assembly level defect, or (2) put back into the first test if classified to be a card level defect. This is the baseline manufacturing policy chosen for the study. An alternate policy commonly used is to pass defects to the next test in sequence. In this way, defects that are caught at, say, test station T_{jk} and which are not removed at assembly level rework would not return to test station T_{jk} but, instead, to test station T_{jk+1}. Only minor changes in the process equations (Figure 5.2) are needed to represent this type of testing policy. Accordingly, Figure 5.3 gives the corresponding equations with the necessary changes.

5.2 Optimization Algorithm

An optimization algorithm has been developed to solve two related problems in the use of screening/debugging tests to reduce the number of part and manufacturing assembly defects. Briefly stated, these two problems are: (1) how

$$X_{i+1jk} = \begin{cases} P_{i+1\ j-1\ N(j-1)} X_{i+1\ j-1\ N(j-1)} + \left(1-P_{ij-1\ N(j-1)}\right)\left(1-F_{ij-1\ N(j-1)}\right)\left(1-R2_{ij-1\ N(j-1)}\right) X_{ij-1\ N(j-1)} \\ \text{for } k=1,\ j>1 \\ \\ P_{i+1\ jk-1} X_{i+1\ jk-1} + \left(1-P_{ijk-1}\right)\left(1-F_{ijk-1}\right)\left(1-R2_{ijk-1}\right) X_{ijk-1}, \text{ for } k>1,\ j\geq 1 \\ \\ \sum_{n=1}^{M} \sum_{m=1}^{N(n)} \left(1-P_{inm}\right) F_{inm} \left(1-R1_{inm}\right) X_{inm}, \text{ for } k=1,\ j=1 \end{cases}$$

Initial Condition

$$X_{111} = ADEF_1 + PDEF$$

$$X_{ij1} = P_{1j-1\ N(j-1)} X_{1j-1\ N(j-1)} + ADEF_j \quad \text{for } j>1$$

$$X_{1jK} = P_{1jk-1} X_{1jk-1} \quad \text{for } K>1$$

Figure 5.3. General Manufacturing Process Equations (Alternate Retest Policy)

to remove a given number of hardware defects (bad parts, assembly errors, design errors, etc.) in the manufacture of a system at a minimum total cost, and (2) given a fixed "not-to-exceed" dollar budget, what screening tests should be conducted to minimize the number of defects getting into the final system.

Unless a manufacturer's resources are severely constrained with respect to testing facilities or the product being manufactured is of a simple nature (e.g., a single level of assembly), the solution to (1) or (2) is not an easy one. The manufacturer not only has a choice of various types of tests (power conditioning, temperature cycling, vibration, etc.) and severities (duration of test, temperature extremes, vibration amplitude, etc.) but must choose where to place his test selections in the manufacturing assembly process. For example, in a situation where there are three types of tests, each one of which has three test parameters and a selection of five values for each parameter, and any combination of the three tests can be conducted at four different levels of assembly

(e.g., card, unit, equipment and system), then there would be a total $5^{36} \approx 1.4\text{x}10^{25}$ possible test sequences, one of which would be optimal.

A given test sequence is considered to be better (more optimal) than another if it provides the same or higher screening strength at a lower cost, or for the same or lower cost it provides a higher screening strength. The measures used in this algorithm to determine optimality are:

TS ≡ (total defects removed)/(total defects introduced)

TC ≡ (average cost per removed defect)

Figure 5.4 outlines the computation procedure for the algorithm. The SDO model provides a selection of five test types (constant temperature, temperature cycling, vibration, power continuous and power cycled) and four assembly levels (card, unit, equipment, system). The number of test parameters are 2, 4, 4, 1, 2 for tests 1 through 5, respectively, and the maximum number of steps (values) for each parameter have been set at 4 (including the parameter values which eliminate the test). Thus, the total number of test sequence combinations possible for the maximum case is:

$$(4^2 \cdot 4^4 \cdot 4^4 \cdot 4 \cdot 4^2)^4 = 4^{52} \approx 2\text{x}10^{31}.$$

At the first step, test T_{11} is combined with test T_{12} to form the sequence $\{u_\ell, v_\ell\}$ $\ell=1, \ldots, 4^6$ defined as follows:

$$u_\ell = TS(\ell, j)[1 - TS(\ell-1, i)] + TS(\ell-1, i) \quad (1)$$

$$v_\ell = TC(\ell, j)\, TS(\ell, j)[1 - TS(\ell-1, i)] + TC(\ell-1, i)/\ell \quad (2)$$

for $i = 1, \ldots, 4^2$ (combinations of T_{11}) and $j = 1, \ldots, 4^4$ (combinations of T_{12}). This sequence is ranked from lowest to highest cost (v_ℓ) and a dominant sequence is formed by removing combinations in which the test strength (u_ℓ) is lower than the preceding combination (i.e., $u_\ell < u_{\ell-1}$). The dominant sequence

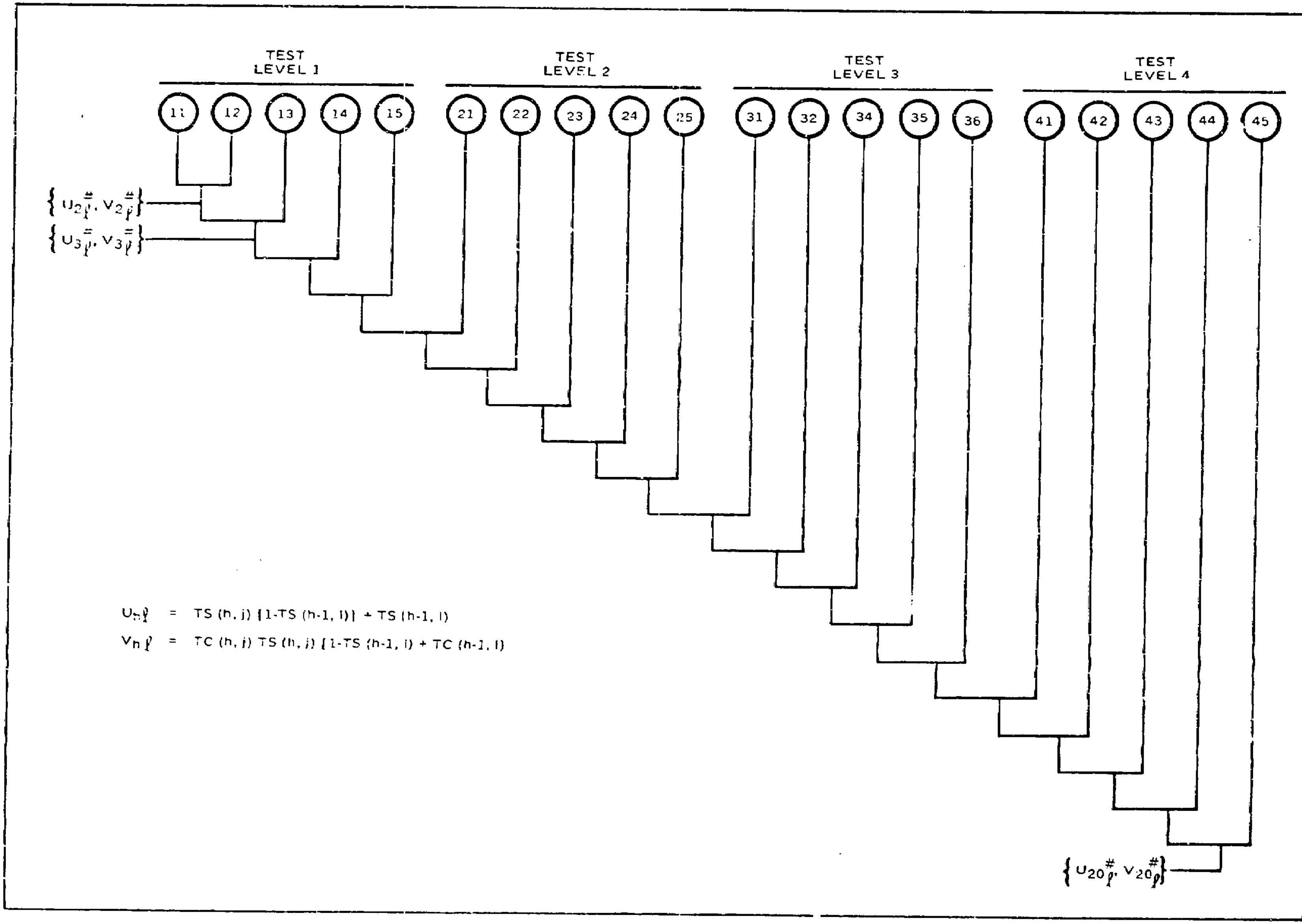


Figure 5.4. Computation Procedure for the Optimization Algorithm

formed in this way (say $\{u^*_\ell, v^*_\ell\}$) provides the input necessary for the next step, i.e.,

$$TS(\ell-1, i) = u^*_\ell$$

and

$$TC(\ell-1, i) = v^*_\ell$$

This dominant sequence is then combined with T_{13} according to equations (1) and (2) above to form the next sequence. The procedure is continued until all test combinations have been exhausted. The final dominant sequence, say $\{u^{\#}\ell, v^{\#}\ell\}$, is therefore optimal in the following sense:

1. If m>n then $u^{\#}_m \geq u^{\#}_n$ and $v^{\#}_m \geq v^{\#}_n$ (i.e., the sequence is monotone never decreasing in both $u^{\#}_\ell$ and $v^{\#}_\ell$)

2. If (u', v') represent the test strength and cost, respectively, of any other sequence of tests which does not belong to $\{u^{\#}_\ell, v^{\#}_\ell\}$, then there is a test sequence that does belong to $\{u^{\#}_\ell, v^{\#}_\ell\}$ which dominates (u', v').

The successively larger number of test sequence combinations produced at each step can also be reduced by eliminating terms from the dominant sequences that are too close to matter. For example, costs and test strengths that differ by less than one percent could be removed and would not appear in a dominant sequence. This would not produce a "pure optimum' solution but would produce a practical "near optimum" solution.

Figure 5.5 gives a flow diagram of the optimization procedure. The procedure has been computerized (written in FORTRAN IV) for processing on an IBM 360/370 computer and consists of a MAIN calling routine and six subroutines which are defined as follows:

DATA – This subroutine reads and writes all input data with the exception of individual test cost parameter values which are read in for each test in the MAIN. Default values for most parameters are also defined in the event no user data is available.

SSPROB – This subroutine: (1) calculates the screening strength probabilities of each of five tests as a function of test parameter values, (2) calculates single cycle test strengths (P_{ijk} values of the previous topic) based on test equipment detection probabilities and the screening strength, and (3) calculates test cost based on the duration of the test.

SCREEN – This routine models the manufacturing process and calculates the total test strength and cost of a specified test sequence.

RANK – This routine ranks a given set of test combinations by cost from lowest to highest.

SEARCH – This routine searches through the optimal sequence for the combination that satisfies the specified requirement (i.e., MTBF requirement or fixed cost requirement).

REPORT – This routine decodes the selected test sequence into the original test parameter values and writes an output report which (1) identifies each test and test parameter value, and (2) summarizes the cost for each test and level of assembly.

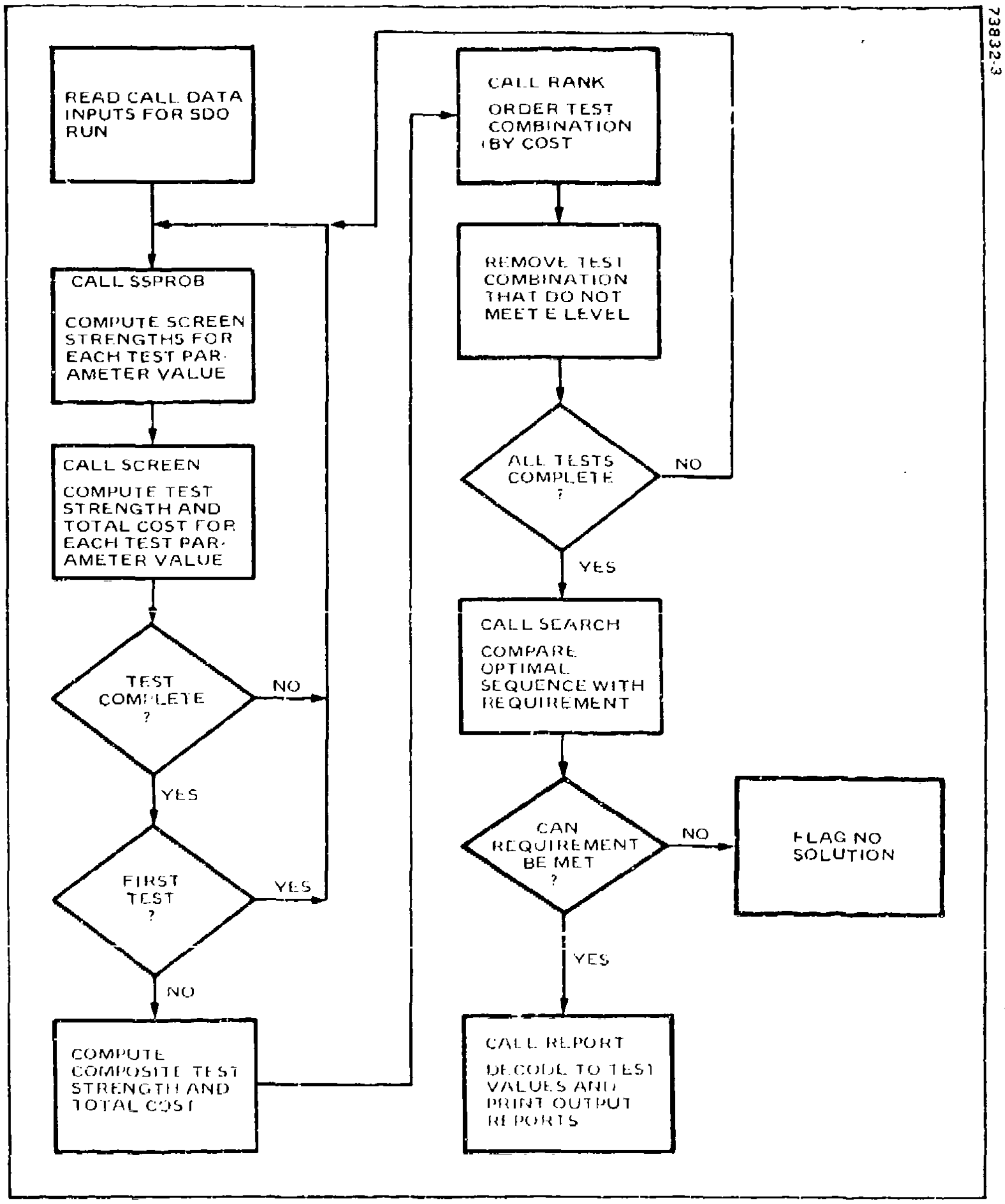


Figure 5.5. Flow Diagram of Optimization Procedure

SECTION 6.0 — PROCEDURES AND EXAMPLES

6.1 Procedure for Using the SDO Model

Data Input Requirements and Fall-back Options

In order to operate the SDO model, certain input data requirements must be provided. Some data must be provided by the user such as an estimate of the system failure rate (e.g., based on a handbook prediction), the customer required failure rate and system complexity (part count). Other data is optionally provided by the user with a default to SDO model supplied values based on study findings. Table 6.1 summarizes the data requirements, parameter symbol, computer input format, units, source and fall-back option. The following paragraphs describe the data requirements and parameters in more detail.

Test Characteristics

The test cost function has the form: CT = A1 + (B1) (HOURS) where A1 and B1 are the fixed and variable costs, respectively, and HOURS represents the duration of the test. CT represents the total cost of conducting the test and is expressed in dollars. The option is exercised whenever B1 is zero. In this case, CT is expressed in hours. The option on fixed test cost (A1 = 0.0) assumes that no large capital investment in test equipment is needed to implement any of the test sequences being considered. The option on variable test costs is based on Hughes experience in testing at various levels of assembly.

Screening strength (SS) is computed automatically using subroutine SSPROB by evaluating the CREDIT (ref. 42) equations for screening strength at selected points of the test parameters. The probability of detecting a defect (P_d) with test equipment is dependent on the screen used, the level of assembly and the number of test rework cycles. P_d is an array defined by: $P_d = P_d$ (I, I1, I2) where $1 \leq I \leq NCYC$ cycles, $1 \leq I1 \leq M$ assembly levels and $1 \leq I2 \leq 5$ tests. If any value of P_d is zero, the default to $P_d = 0.75$ is exercised.

The parameters of each test are sequenced through values in the optimization process described in the previous section. The minimum and maximum limits for each test parameter are optionally specified by the user. These limits are denoted by $AMIN_{jk}$ and $AMAX_{jk}$ representing the minimum and maximum limits of the kth parameter of the jth test. The standard values of these limits are provided by the SDO model as default values in the following table.

Test Parameter	Type of Test				
	Constant Temperature	Cycled Temperature	Vibration	Constant Power	Cycled Power
Parameter No. 1	Temp Extreme	Upper Temp	G-Level	Time	Time
max	70°C	70°C	6	168	8 hours
min	-55°C	25°C	1	0	0 hours
Parameter No. 2	Test Time	Lower Temp	Time	-	Cycles
max	170 hours	-50°C	2 hours	-	168
min	0 hours	-25°C	0 hours	-	3
Parameter No. 3	-	Temp Rise	Temp	-	-
max	-	10°C/min	25°C	-	-
min	-	0°C/min	25°C	-	-
Parameter No. 4	-	Cycles	Cycles	-	-
max	-	64	64	-	-
min	-	10	10	-	-

Manufacturing Process - Fixed rework cost is specified as a factor of the variable rework cost which is furnished by the user. If the variable rework cost (B2 for card level and B3 for higher levels) is zero, the SDO model default is exercised as follows:

Location of Repair	Manufacturing Assembly Level			
	1	2	3	4
Card level (B2)	0.5	9.46	51.5	63.0
Higher Assembly Level (B3)	0.1	3.67	45.5	57.0

The above quantities are expressed in man-hours and are averages based on a wide variety of card and assembly types (see page 42).

Fraction defective sent to card level repair (F) is the expected fraction of defects occurring at higher assembly levels which are sent to the card level

TABLE 6.1. Input Data Requirements/Options

Data Requirements	Prog Symbol	Input Format	Units	Source	Fall-back Option
Test Characteristics					
Fixed Test Cost	A1	Real	Dollars	User	Assumed zero
Variable Test Cost	B1	Real	Dollars/Hour	User	Provided as a function of test duration
Screening Strength	SS	–	–	SDO Model	None
Detection Probability	P	–	–	User	Default to 0.75
Test Parameter Limits	$AMIN_{jk}$, $AMAX_{jk}$	Real	(See test description)	User	Standard ranges provided by SDO model
Mfg Process					
Fixed Rework Cost	–	–	–	Function of variable cost	None
Variable Rework Cost	B2, B3	Real	Hours	User	Provided as a function of the rework level
Fraction Defectives to Card Rework	F	Real	–	User	Provided as a function of the rework level
Fraction Defectives Removed at Card Rework	R1	Real	–	User	Default to 0.5
Fraction Defectives Removed at Assy Rework	R2	Real	–	User	Default to 0.5
Number of Assy Levels	M	Integer	–	User	4-levels maximum
Maximum Number of Test-Rework Cycles	NCYC	Integer	–	User	10-cycles maximum
Assy Defects	ADEF	Real	Fraction of total parts	User	Default to 2.3% of total parts for each level
Part Quality Defects	PDEF	Real	Fraction of total parts	User	Default to 1.0% of total parts

TABLE 6.1. Input Data Requirements/Options (Continued)

Data Requirements	Prog Symbol	Input Format	Units	Source	Fall-back Option
System Description					
Complexity (total parts)	NPARTS	Integer	–	User	None
Predicted Failure Rate*	FRM	Real	per million hours	User	None
Field Stress (3-year operation)**:					
Temperature Rise Time	$PMAX_{21}$	Real	Deg C/min	User	Field strength defaults to 1.0 (i.e., the system is assumed to reach maturity in 3 years)
Duration of Vibration	$PMAX_{32}$	Real	Hours	User	
Duration of on-off cycle	$PMAX_{51}$	Real	Hours	User	
Number of Cycles	$CYCMAX_{jk}$	Real	-	User	
Program					
Option A:					
Required Failure Rate	FRF	Real	per million hours	User	None
Option B:					
Cost Budget	CREQD	Real	Dollars	User	If cost defaults are used, cost budget must be in hours
Number Test Values	ITV	Integer	–	User	Recommend 4 maximum
Tolerance	E	Real	–	User	Recommand 0.01 minimum

*Required for program option A only

**Three types of field stress are provided : (1) temperature cycling, (2) vibration and (3) power on-off cycling.

for repair. All other defects are repaired at the assembly level in which detection took place. F is a function of the screen used, the level of assembly and number of test rework cycles. If zero values are provided for by the user, the SDO model default is exercised as follows:

	Manufacturing Assembly Level			
	1	2	3	4
F	1.0	0.23	0.43	0.65

The above values are based on Hughes' manufacturing experience at the various assembly levels.

Fraction defectives corrected (R1 for the card level and R2 for the higher assembly level) are functions of the screen used, the level of assembly and the number of test-rework cycles. If zero values are provided by the user for R1 or R2 the SDO model default is exercised (i.e., R1 = 0.5 and R2 = 0.5).

The number of assembly levels (M) is based on a card-unit-equipment-system assembly structure. A value of M equal to 4 will use the complete structure and smaller values of M will use a limited structure. For example, a user may only build to the equipment level in which case he would set M = 3.

The number of defects entering the process is based on fraction defectives for parts (PDEF) and assembly errors (ADEF), the total number of parts used in the system and the number of systems being produced. PDEF is input as a fraction of the total parts (NPARTS) and defaults to 0.01 (i.e., 1% of the total number of parts used in system) when user data is not available. Similarly, ADEF defaults to 0.023 (2.3% of the total parts) for all assembly levels when user data is not available. The maximum number of test-rework cycles (NCYC) a single defect would see is dependent upon the complexity and testability of the hardware. Since the number of defects is based on the total parts required for the system, NCYC should be sufficiently large to exhaust the process (i.e., no defects remaining in rework), otherwise the systems being assembled are not complete.

System Description/Program Data

System description data is required whenever the test sequence selection is driven by a product reliability requirement (Option A). In this case the model requires the predicted failure rate (FRM) for the "mature" system (e.g., in accordance with MIL-HDBK-217), the required (by a customer specification) system failure rate (FRF) and the total number of parts (NPARTS) used in all systems being produced. If cost is the driving factor in the test sequence selection (Option B), NPARTS and the total cost budget (CREQD) are required. CREQD includes the budget for the total test cost plus the total rework cost necessary to assemble all systems.

Field stress is characterized by three "tests": temperature cycling, vibration, and power cycling. Thus, defects that are present in the system at delivery will continue to show up in the field (together with random failures) until the system reaches "Maturity" (i.e., no more defects). At this point in time, the system still fails but only due to "random" failures. All latent defects have been removed by the field stress.

The SDO model defaults to a field stress (i.e., a "test" strength) of 1.0 and three operating years to maturity (26,280 hours). The user can optionally provide the estimated amount of field stress the system will experience until maturity is reached by specifying $PMAX_{jk}$ for the appropriate tests and $CYCMAX_{jk}$.

The number of test values (ITV) represents the number of values each test parameter takes on in computing screening strengths for each test. The value of ITV has a significant effect of the computer running time and core requirements. It is, therefore, recommended that the value of ITV not exceed 4. The tolerance (E) has a similar effect on computer running time and core requirements and may be varied with ITV to get better usage of the model. It is recommended, however, that E does not go below 0.01. This value corresponds to eliminating from further consideration those test sequences that are closer than 1% in cost or test strength at each step of the optimization process.

Procedure and Examples

The examples given in this section detail the step-by-step procedure for using the SDO model. Example 1 describes the procedure for determining the optimal screen under a fixed cost constraint and Example 2 describes the procedure for determining the least cost screen for meeting a reliability requirement. The following general operational description applies to all procedures for processing input data and execution of the SDO model on an IBM 360/370 computer.

Job Control Language (JCL) - The following statements are required for allocating storage and assignment of input data files:

```
//TF19556A  JOB  (2,              GENERATED  JOB STATEMENT
// 606,T09520,00,42,SNUMB),'K218,JAMES, L E        ',CLASS=B,REGION=500K,
//                 NOTIFY=TF19556,
//                 MSGLEVEL=(1,1)
/*MAIN    ORG=RM029
// EXEC  FORTGO,GOPGM=TEMPNAME,TIME=10
//STEPLIB DD DISP=SHR,DSN=TF19556, SD2.MAIN.LOAD
//GO,FT04F001  DD  DISP=SHR,DSN=TF19556.PROGRM.DATA
//GO,FT11F001  DD  DISP=SHR,DSN=TF19556.PD.DATA
//GO,FT08F001  DD  DISP=SHR,DSN=TF19556.F.DATA
//GO,FT09F001  DD  DISP=SHR,DSN=TF19556.R.DATA
```

```
//GO, FT10F001 DD DISP=SHR, DSN=TF19556.AB.DATA
//GO, FT12F001 DD DISP=SHR, DSN=TF19556. LIMITS. DATA
//GO, FT13F001 DD DISP=SHR, DSN-TF19556.OPS.DATA
```

Definition of Input Data Sets - The above JCL creates the data sets noted below. The asterisks denote that the associated parameter has a default value and the numbers in the parentheses give the maximum dimension for arrays.

File 04 PROGRM - This data set contains data for the parameters NCYC, M, NPARTS, CREQD, E, ITV, FRF, FRM, PDEF*, ADEF(5)*, N(5), B2, B3.

File 08 F- This data set contains data for the array F(10, 4, 5)*

File 09 R - This data set contains data for the arrays R1 (10, 4, 5)* and R2 (10, 4, 5)*

File 10 AB - This data set contains data for the parameters A1*, B1*

File 11 PD - This data set contains data for the array P (10, 4, 5)*

File 12 LIMITS - This data set contains data for upper and lower limits on each test parameter

File 13 OPS - This data set contains test parameter data for simulating field stress

All files must be filled. If the default is to be exercised, zero values for all parameters and array elements must be used. The input form for each data set is "unformatted" (i.e., the values for each record are simply separated by commas - this is illustrated in the examples given below).

Diagnostics - If the number of combination of test sequences becomes too large for a particular choice of number of test parameter values (ITV) and tolerance (E), a subscript error check will occur. The error condition can be removed by: (1) increasing the dimension on the appropriate arrays, (2) decreasing the value of ITV, and/or increasing the value of E.

Output Reports - All input data used in the SDO model is printed out in table form. If defaults are exercised the default values are printed in the tables. The optimal test sequence is also printed out in table format and the following table gives a cross-reference index between test parameter number and definition for each test:

Test Parameter Cross Reference

	Test Parameter			
	No. 1	No. 2	No. 3	No. 4
Constant Temperature (CT)	Temp Extreme (TA) °C	Test Time (TT) hours	–	–
Cycled Temperature (CYT)	Upper Temp (TU) °C	Lower Temp (TL) °C	Temp Rise (TR) °C per minute	Number cycles (CY)
Vibration (VIB)	Vibration G-level (V)	Time (TM) hours	Temp (TV) °C	Number cycles (CY)
Constant Power (CP)	Time (TM) hours	–	–	–
Cycles Power (CYCP)	Time (TM) hours	Number cycles (CY)	–	–

6.2 Fixed Cost-Optimum Screen

A ground display equipment manufacturer has a limited budget for funding a test-conditioning rework effort during production and, therefore, desires to minimize the number of defects getting into the final production systems and still remain within budget.

Step 1 - Assembly Required Data for Coding.

NCYC - Number of test-rework cycles is set at 10 as adequate to exhaust the process.

M - The number of manufacturing assembly levels is three: card assembly, unit assembly and equipment assembly.

NPARTS - The display contains a total of 10,000 parts per system and 60 systems are planned for production (i.e., NPARTS = 600000).

CREQD - The total cost budget for testing and rework is $500,000.

E - Test screens that are closer than 1% in cost are considered to be equal (i.e., E = 0.01).

ITV - Three values of a test parameter are felt to be adequately sensitive (i.e., ITV = 3).

FRF, FRM - PMAX$_{jk}$ and CYCMAX$_{jk}$ These parameters are set to zero since the cost option is being used (i.e., FRF = 0.0, FRM = 0.0, PMAX$_{jk}$ = 0.0, and CYCMAX$_{jk}$ = 0.0)

AMAX$_{jk}$, AMIN$_{jk}$ The SDO model defaults are used for these parameters.

PDEF The average quality level of parts used in the display is 1.5% defective based on the manufacturer's field usage history.

ADEF - The manufacturer's production records show that he can expect 0.2%, 0.3%, and 0.3% defectives due to assembly errors, wiring errors and generally poor workmanship at the card, unit, and equipment levels, respectively.

P - The detection probabilities of the test equipment used by test department is assumed to be the same as the SDO model default value (i.e., P = 0.75).

F - The manufacturer has found that 80% of unit and equipment failures isolate to a card failure. All others are unit and equipment level assembly/wiring errors.

R1 - Card level repair records show that 80% of the defects are removed at each rework cycle.

R2 - Assembly level repair records show that 50% of the defects are removed on each rework cycle.

B2, B3 - The average repair costs per defect are given (in dollars) as follows:*

Type of Repair \ Level	Card Test	Unit Test	Equipment Test
Card (B2)	5.	60.	250.
Assembly (B3)	5.	25.	60.

A1, B1 - The average test cost for level are given below in dollars for A1 and dollars per hour for B1 as follows:

*The default option could also be used in which case the results would be expressed in hours rather than dollars (see page 54).

Test Cost	CT			CYCT			VIB			CP			CYCP		
	C	U	E	C	U	E	C	U	E	C	U	E	C	U	E
Fixed Cost (A1)	225.	250.	250.	225.	250.	250.	225.	250.	250.	100.	250.	100.	225.	225.	225.
Var Cost (B1)	10.	10.	10.	25.	25.	25.	25.	25.	25.	10.	10.	10.	25.	25.	25.

C: card level testing, U: unit level testing, E: equipment level testing

Step 2 - Coding Input Data. Based on a standard 80-column IBM card, the input for each data set in this example is specified below. The order is the same as in Step 1 and each line represents a single record.

File 04 (PROGRM)

Col. No. 1

```
10,3,600000,500000,.01,3,0.,0.

.015
.002
.003
.003

5.,5.
5.,5.
5.,5.
5.,5.
5.,5.
60.,25.
60.,25.
60.,25.
60.,25.
60.,25.
250.,60.
250.,60.
250.,60.
250.,60.
250.,60.
```

File 11 (PD)

Col. No. 1

```
0.
0.
.
.        fifteen entries
.
0.
```

File 08 (F)

Col. No. 1

```
.4
.4
.
.        fifteen entries
.
.4
```

File 09 (R)

Col. No. 1

```
↓
  .8,.5 ⎫
  .8,.5 ⎪
  . .   ⎬ fifteen entries
  . .   ⎪
  . .   ⎪
  .8,.5 ⎭
```

File 10 (AB)

Col. No. 1

```
↓
  225.,10.
  225.,25.
  225.,25.
  100.,10.
  225.,25.
  250.,10.
  250.,25.
  250.,25.
  250.,10.
  225.,25.
  250.,10.
  250.,25.
  250.,25.
  100.,10.
  225.,25.
```

File 12 (LIMITS)

Col. No. 1

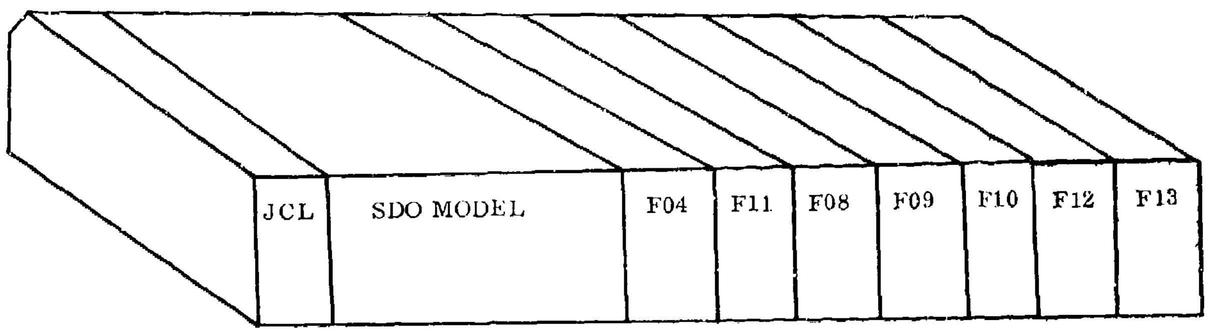
```
↓
  0.,0.
   .
   .      13 entries
   .
  0.,0.
```

File 13 (OPS)

Col. No. 1

```
↓
  0.,0.
  0.,0.
  0.,0.
```

Step 3 - Prepare Card Deck for Processing. The card deck must be put in the following order for processing:



| Step 4 | - Output Reports. The output reports for this example are given in Tables 6.2 through 6.9. Table 6.10 gives the optimal (highest test strength) screening sequence for the budget specified. Therefore, the best the manufacturer can do for the given budget is a test strength of .7727 which indicates that he will eliminate 77.3% of the defects per equipment at a total cost of $494,240 or $8,237 per system.

6.3 Fixed Reliability - Minimum Cost

A radar manufacturer has a customer requirement for a 300-hour system MTBF. Based on MIL-HDBK-217 he estimates his radar system has a mature MTBF of 500 hours. The manufacturer would like to determine the minimum amount of screening (i.e., least cost) which would allow him to meet his customer's requirement. In addition to choosing screening tests, the manufacturer also has a choice of using higher quality parts in his system which would increase the mature system MTBF to 1000 hours but would increase the cost per system. However, this action would also reduce the number of part defects entering the manufacturing process thereby reducing test rework costs. The manufacturer's problem, therefore, is a tradeoff between part quality and amount of test screening to determine (1) whether he should buy the more expensive parts to use in his system, and (2) what screens should he implement to meet the required 300-hour MTBF.

| Step 1 | - Assemble Required Data for Coding.

NCYC - Number of test rework cycles is set at 10.

M - Four manufacturing levels are used: card, unit, equipment and system.

NPARTS - The radar contains a total of 20,000 parts per system and 40 systems are planned for production (i.e., NPARTS = 800000)

CREQD - Not required for the option (i.e., CREQD = 0.0).

E - Test screens that are closer than 2% in cost are considered equal (i.e., E = .02)

ITV - Three values of the test parameters are needed (i.e., ITV = 3) to provide the necessary sensitivity.

FRF (40 systems) - $133320./10^6$ hours (300-hour MTBF per system) customer requirement for 40 systems.

FRM (40 systems) - $80000./10^6$ hours (500 hours MTBF for a mature system using medium quality parts)

- $40000./10^6$ hours (1000-hour MTBF for a mature system using high quality parts)

TABLE 6.2

TABLE A - PROGRAM DATA

NCYC	M	(PDEF.NPARTS)	CREQD	E	ITV	FRF	FRM
10	3	9000.	500000.00	0.010000	3	0.0	0.0

TABLE 6.3

TABLE B - TEST AND ASSEMBLY DATA

ASSEMBLY LEVEL	NUMBER OF SCREENS	EXPECTED NUMBER OF ASSEMBLY DEFECTS
1	5	1200.
2	5	1800.
3	5	1800.

TABLE 6.4

TABLE C - DETECTION PROBABILITIES FOR TEST EQUIPMENT

.750000000	.750000000	.750000000	.750000000	.750000000	.750000000
.750000000	.750000000	.750000000	.750000000	.750000000	.750000000
.750000000					

TABLE 6.5

TABLE D - FRACTION OF DEFECTS REQUIRING PRIMARY LEVEL (CARD ASSY) REWORK

.399999976	.399999976	.399999976	.399999976	.399999976	.399999976	.399999976
.399999976	.399999976	.399999976	.399999976	.399999976	.399999976	.399999976
.399999976						

TABLE 6.6

TABLE E - FRACTION OF DEFECTS REMOVED AT THE PRIMARY LEVEL PER REWORK/RETEST CYCLE

.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	.800000012
.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	.800000012
.800000012						

TABLE 6.7

TABLE F - FRACTION OF DEFECTS REMOVED AT THE HIGHER ASSEMBLY LEVEL PER REWORK/RETEST CYCLE

.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	.500000000
.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	.500000000
.500000000						

TABLE 6.8

TABLE G - PRIMARY LEVEL REWORK COST PER CYCLE

5.00000000	5.00000000	5.00000000	5.00000000	5.00000000	60.0000000	60.0000000
60.0000000	60.0000000	60.0000000	250.000000	250.000000	250.000000	250.000000
250.000000						

TABLE 6.9

TABLE H - HIGHER ASSEMBLY LEVEL REWORK COST PER CYCLE

5.00000000	5.00000000	5.00000000	5.00000000	5.00000000	25.0000000	25.0000000
25.0000000	25.0000000	25.0000000	60.0000000	60.0000000	60.0000000	60.0000000
60.0000000						

TABLE 6.10

TEST SEQUENCE	TYPE	NO. 1	NO. 2	NO. 3	NO. 4	TOTAL COST
		TEST DESCRIPTION PARAMETER VALUE				
LEVEL NO. 1						329244.50
TEST NO. 1	CT	70.00	170.00	0.0	0.0	27561.11
TEST NO. 2	CYT	47.50	-50.00	10.00	37.00	137318.06
TEST NO. 3	VIB	6.00	1.00	25.00	64.00	28512.21
TEST NO. 4	CP	84.00	0.0	0.0	0.0	20249.07
TEST NO. 5	CYP	8.00	85.50	0.0	0.0	115604.12
LEVEL NO. 2						164995.06
TEST NO. 1	CT	0.0	0.0	0.0	0.0	0.0
TEST NO. 2	CYT	25.00	-25.00	10.00	64.00	141504.56
TEST NO. 3	VIB	3.50	2.00	25.00	37.00	23490.55
TEST NO. 4	CP	0.0	0.0	0.0	0.0	0.0
TEST NO. 5	CYP	0.0	0.0	0.0	0.0	0.0
LEVEL NO. 3						0.0
TEST NO. 1	CT	0.0	0.0	0.0	0.0	0.0
TEST NO. 2	CYT	0.0	0.0	0.0	0.0	0.0
TEST NO. 3	VIB	0.0	0.0	0.0	0.0	0.0
TEST NO. 4	CP	0.0	0.0	0.0	0.0	0.0
TEST NO. 5	CYP	0.0	0.0	0.0	0.0	0.0
TOTAL COST						494239.56

TOTAL SEQUENCE TEST STRENGTH = 0.951277
0.772650

$PMAX_{jk}$, $CYCMAX_{jk}$	-	Over a 3-year field usage period the radar is expected to experience temperature cycling and power on-off cycling characterized by approximately 1095 cycles of power (on:2.5 hours and off:2.5 hours, i.e. $PMAX_{51}$ = 5 hours and $CYCMAX_{52}$=1095) and 1095 cycles of temperature (at 2°C/min. between extremes, i.e., $PMAX_{23}$ = 2 and $CYCMAX_{24}$ = 1095.
PDEF	-	The average part quality is estimated at 1% defects for existing parts and 0.5% for high quality parts.
ADEF	-	The average percentage of assembly type defects from the manufacturing process is estimated at 1.2% of the total number of parts per system (i.e., 0.3% at each of four assembly levels).
R1	-	Card level repair records show that 80% of the defects are removed on each rework cycle.
R2	-	Assembly level repair records show that 50% of the defects are removed on each rework cycle.
P, F, B2, B3, A1, B1	-	The manufacturer decided to use SDO model defaults for these parameters in this tradeoff.
$AMAX_{jk}$, $AMIN_{jk}$	-	The temperature extremes used in the SDO model were not adequate for the radar system so these were extended to -55°C and 125°C. All other default test values were considered adequate.
Step 2	-	Coding Input Data

Case A: Existing quality parts

File 04 (PROGRM)

Col. No. 1

```
10, 4, 800000, 0, .01, 3, 133320., 80000.

.010
.003
.003
.003
.003
0.,0.  )
0.,0.  |
0.,0.  |
.      } 20 entries
.      |
.      |
0.,0.  )
```

File 11 (PD)

(All 20 values set to zero)

File 08 (F)

(All 20 values set to zero)

File 09 (R)

```
Col. No. 1
   ↓
   .8,.5  ⎫
   .8,.5  ⎪
   .      ⎬ 20 entries
   .      ⎪
   .      ⎪
   .8,.5  ⎭
```

File 10 (AB)

(All 20 values set to zero)

File 12 (LIMITS)

```
Col. No. 1
   ↓
   125.,-55.
   0.,0
   125.,25.
   -55.,-25
   0.,0.   ⎫
     .     ⎪
     .     ⎬ 9 entries
     .     ⎪
   0.,0    ⎭
```

File 13 (OPS)

```
Col. No. 1
   ↓
   2.,1095.
   0.,0
   5.,1095.
```

Step 3 - Prepare Card Deck for Processing

(Same as previous example)

| Step 4 | - Output Reports. The output reports for Case A are given in Tables 6.11 through 6.18. Table 6.19 gives the optimal screening sequence which will meet customer MTBF requirements at minimum cost using medium quality parts. The test strength of the total sequence will remove an estimated 95% of the total defects entering the manufacturing process. Cost is in terms of total labor hours for test and rework effort for the total program (i.e., manufacturer of 40 radar systems). The average cost per system is 4364 hours in test/rework labor.

Case B: High quality parts

The only change to the input data is in File 04 (PROGRM) which is shown below:

File 04 (PROGRM)

Col. No. 1

```
↓
10,4,800000.,0,.02,3,133320.,40000.
.005
.003
.003
.003
.003
0.,0.  ┐
0.,0.  │
.      │
.      ├ 20 entries
.      │
0.,0.  ┘
```

The output reports for Case B are given in Table 6.20 through 6.27. Table 6.28 gives the optimal sequence for this case.

TABLE 6.11

TABLE A - PROGRAM DATA

NCYC	M	(PDEF.NPARTS)	CREQD	E	ITV	FRF	FRM
10	4	8000.	0.0	0.020000	3	133320.00	80000.00

TABLE 6.12

TABLE B - TEST AND ASSEMBLY DATA

ASSEMBLY LEVEL	NUMBER OF SCREENS	EXPECTED NUMBER OF ASSEMBLY DEFECTS
1	5	2400.
2	5	2400.
3	5	2400.
4	5	2400.

TABLE 6.13

TABLE C - DETECTION PROBABILITIES FOR TEST EQUIPMENT

.750000000	.750000000	.750000000	.750000000	.750000000	.750000000	.750000000
.750000000	.750000000	.750000000	.750000000	.750000000	.750000000	.750000000
.750000000	.750000000	.750000000	.750000000	.750000000	.750000000	

TABLE 6.14

TABLE D - FRACTION OF DEFECTS REQUIRING PRIMARY LEVEL (CARD ASSY) REWORK

1.00000000	1.00000000	1.00000000	1.00000000	1.00000000	.230000019	.230000019
.230000019	.230000019	.230000019	.430000007	.430000007	.430000007	.430000007
.430000007	.649999976	.649999976	.649999976	.649999976	.649999976	

TABLE 6.15

TABLE E-FRACTION OF DEFECTS REMOVED AT THE PRIMARY LEVEL PER REWORK/RETEST CYCLE

.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	.800000012
.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	.800000012
.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	

TABLE 6.16

TABLE F-FRACTION OF DEFECTS REMOVED AT THE HIGHER ASSEMBLY LEVEL PER REWORK/RETEST CYCLE

.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	.500000000
.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	.500000000
.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	

TABLE 6.17

TABLE G-PRIMARY LEVEL REWORK COST PER CYCLE

.500000000	.500000000	.500000000	.500000000	.500000000	9.46000004	9.46000004
9.46000004	9.46000004	9.46000004	51.5000000	51.5000000	51.5000000	51.5000000
51.5000000	63.0000000	63.0000000	63.0000000	63.0000000	63.0000000	

TABLE 6.18

TABLE H-HIGHER ASSEMBLY LEVEL REWORK COST PER CYCLE

.100000024	.100000024	.100000024	.100000024	.100000024	3.67000008	3.67000008
3.67000008	3.67000008	3.67000008	45.5000000	45.5000000	45.5000000	45.5000000
45.5000000	57.0000000	57.0000000	57.0000000	57.0000000	57.0000000	

TABLE 6.19

TEST SEQUENCE			TYPE	TEST DESCRIPTION PARAMETER VALUE NO. 1	NO. 2	NO. 3	NO. 4	TOTAL COST
LEVEL NO. 1								62108.79
TEST	NO.	1	CT	0.0	0.0	0.0	0.0	0.0
TEST	NO.	2	CYT	25.00	-40.00	10.00	64.00	25021.56
TEST	NO.	3	VIB	6.00	2.00	25.00	64.00	6063.25
TEST	NO.	4	CP	84.00	0.0	0.0	0.0	3557.58
TEST	NO.	5	CYP	8.00	168.00	0.0	0.0	27466.40
LEVEL NO. 2								65752.94
TEST	NO.	1	CT	125.00	170.00	0.0	0.0	8315.57
TEST	NO.	2	CYT	125.00	-25.00	5.00	64.00	24673.20
TEST	NO.	3	VIB	6.00	2.00	25.00	37.00	5297.86
TEST	NO.	4	CP	0.0	0.0	0.0	0.0	0.0
TEST	NO.	5	CYP	8.00	168.00	0.0	0.0	27466.34
LEVEL NO. 3								23975.28
TEST	NO.	1	CT	0.0	0.0	0.0	0.0	0.0
TEST	NO.	2	CYT	75.00	-40.00	5.00	64.00	23975.28
TEST	NO.	3	VIB	0.0	0.0	0.0	0.0	0.0
TEST	NO.	4	CP	0.0	0.0	0.0	0.0	0.0
TEST	NO.	5	CYP	0.0	0.0	0.0	0.0	0.0
LEVEL NO. 4								22709.52
TEST	NO.	1	CT	0.0	0.0	0.0	0.0	0.0
TEST	NO.	2	CYT	25.00	-25.00	10.00	37.00	22709.52
TEST	NO.	3	VIB	0.0	0.0	0.0	0.0	0.0
TEST	NO.	4	CP	0.0	0.0	0.0	0.0	0.0
TEST	NO.	5	CYP	0.0	0.0	0.0	0.0	0.0
TOTAL COST								174546.37

TOTAL SEQUENCE TEST STRENGTH = 0.951277

TABLE 6.20

TABLE A - PROGRAM DATA

NCYC	M	(PDEF. NPARTS)	CREQD	E	ITV	FRF	FRM
10	4	4000.	0.0	0.020000	3	133320.00	40000.00

TABLE 6.21

TABLE B - TEST AND ASSEMBLY DATA

ASSEMBLY LEVEL	NUMBER OF SCREENS	EXPECTED NUMBER OF ASSEMBLY DEFECTS
1	5	2400.
2	5	2400.
3	5	2400.
4	5	2400.

TABLE 6.22

TABLE C - DETECTION PROBABILITIES FOR TEST EQUIPMENT

.750000000	.750000000	.750000000	.750000000	.750000000	.750000000	.750000000
.750000000	.750000000	.750000000	.750000000	.750000000	.750000000	.750000000
.750000000	.750000000	.750000000	.750000000	.750000000	.750000000	

TABLE 6.23

TABLE D - FRACTION OF DEFECTS REQUIRING PRIMARY LEVEL (CARD ASSY) REWORK

1.00000000	1.00000000	1.00000000	1.00000000	1.00000000	.230000019	.230000019
.230000019	.230000019	.230000019	.430000007	.430000007	.430000007	.430000007
.430000007	.649999976	.649999976	.649999976	.649999976	.649999976	

TABLE 6.24

TABLE E-FRACTION OF DEFECTS REMOVED AT THE PRIMARY LEVEL PER REWORK/RETEST CYCLE

.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	.800000012
.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	.800000012
.800000012	.800000012	.800000012	.800000012	.800000012	.800000012	

TABLE 6.25

TABLE F-FRACTION OF DEFECTS REMOVED AT THE HIGHER ASSEMBLY LEVEL PER REWORK/RETEST CYCLE

.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	.500000000
.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	.500000000
.500000000	.500000000	.500000000	.500000000	.500000000	.500000000	

TABLE 6.26

TABLE G-PRIMARY LEVEL REWORK COST PER CYCLE

.500000000	.500000000	.500000000	.500000000	.500000000	9.46000004	9.46000004
9.46000004	9.46000004	9.46000004	51.5000000	51.5000000	51.5000000	51.5000000
51.5000000	63.0000000	63.0000000	63.0000000	63.0000000	63.0000000	

TABLE 6.27

TABLE H-HIGHER ASSEMBLY LEVEL REWORK COST PER CYCLE

.100000024	.100000024	.100000024	.100000024	.100000024	3.67000008	3.67000008
3.67000008	3.67000008	3.67000008	45.5000000	45.5000000	45.5000000	45.5000000
45 5000000	57.0000000	57.0000000	57.0000000	57.0000000	57.0000000	

TABLE 6.28

TEST SEQUENCE	TYPE	TEST DESCRIPTION PARAMETER VALUE NO. 1	NO. 2	NO. 3	NO. 4	TOTAL COST
LEVEL NO. 1						45346.00
TEST NO. 1	CT	0.0	0.0	0.0	0.0	0.0
TEST NO. 2	CYT	125.00	-55.00	10.00	37.00	18346.68
TEST NO. 3	VIB	6.00	2.00	25.00	64.00	4414.02
TEST NO. 4	CP	84.00	0.0	0.0	0.0	2589.91
TEST NO. 5	CYP	8.00	168.00	0.0	0.0	19995.40
LEVEL NO. 2						51513.27
TEST NO. 1	CT	125.00	170.00	0.0	0.0	6053.69
TEST NO. 2	CYT	75.00	-25.00	5.00	64.00	17159.95
TEST NO. 3	VIB	6.00	1.00	25.00	64.00	3646.78
TEST NO. 4	CP	168.00	0.0	0.0	0.0	4657.46
TEST NO. 5	CYP	8.00	168.00	0.0	0.0	19995.39
LEVEL NO. 3						24152.43
TEST NO. 1	CT	125.00	170.00	0.0	0.0	6053.68
TEST NO. 2	CYT	25.00	-25.00	10.00	64.00	18098.75
TEST NO. 3	VIB	0.0	0.0	0.0	0.0	0.0
TEST NO. 4	CP	0.0	0.0	0.0	0.0	0.0
TEST NO. 5	CYP	0.0	0.0	0.0	0.0	0.0
LEVEL NO. 4						0.0
TEST NO. 1	CT	0.0	0.0	0.0	0.0	0.0
TEST NO. 2	CYT	0.0	0.0	0.0	0.0	0.0
TEST NO. 3	VIB	0.0	0.0	0.0	0.0	0.0
TEST NO. 4	CP	0.0	0.0	0.0	0.0	0.0
TEST NO. 5	CYP	0.0	0.0	0.0	0.0	0.0
TOTAL COST						121011.56

TOTAL SEQUENCE TEST STRENGTH = 0.892764

Comparing the results of Case A and Case B shows that a total savings of 53,535 hours can be realized in test and rework costs of using the higher quality parts. This amounts to a savings per system of 1338 hours. If a labor rate of $20 per hour is used, $26,760 per system is saved. This amount must of course be offset by the increased cost per system using the higher quality parts. If there is still a significant savings, the decision would be to use the higher quality parts and screen according to Table 6.28. If there is no savings, the decision would be to use the medium quality parts and screen according to Table 6.19.

It should be noted (also see p. 48) that the tests given in the tables for a given level of assembly can, of course, be conducted at the same time which would further reduce associated testing costs.

SECTION 7.0 – RECOMMENDATIONS AND CONCLUSIONS

In any development of an SDC model the key variables are test costs, (fixed and variable), screening strength (SS) and probability of detection (P_d). In this present study we were able to obtain quantitative information on all three of these parameters.

However, the issue is far from closed on the variables screening strength and probability of detection. Good estimates of these two parameters are required for any tradeoff studies regarding the cost-effectiveness of screening and debugging tests. Unfortunately, beyond this present study, little has been done regarding quantitative functions for SS and P_d. P_d, of course, is an "equal" component of test strength (TS). It is entirely conceivable that analytic, or at least quantitative, models for P_d can be developed. The development would proceed much along the lines of a failure modes and effects analysis. Types of failures could be identified, the type of test equipment needed to detect them and so on. The determination of SS might not be as "easy" as P_d but it is clearly worth further study. In view of the difficulty in measuring SS, fairly carefully designed experiments would be required to randomize out the superfluous effects such as the (unknown) number of defects entering the screen. Also, care should be taken to control or design out P_d for the determination of SS.

It is recommended that, as part of applying the model results, the techniques of monitoring and controlling the screening/debugging process be further studied and developed and that a data base be built for verification and refinement of the model inputs.

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APPENDIX A

A. 1 UCLA-Biomedical Computer Program (BMD07R)

In the computation of Test Strength for Card/Unit Level and Equipment/System Level, and determining the Test Strength Relationship to Number of Subcontractors, the BMD07R computer program was used to find various parameter values. BMD07R is a nonlinear least squares regression program that incorporates with the canned routine the user supplied functional equation, partial derivatives, parameters and variables. Sample functions and variable values along with estimates for the parameters are used in an iteration scheme designed to converge to the parameter values. The UCLA BMD07R program is accessed by the IBM 370 system through use of the cataloged procedure, BMDT, which provides the necessary job control language. These programs use the FORTRAN IV language.

A. 2 General Curve Plotting (QKPLOT):

A curve plot was given in Figure 4. 1 under the Computation of Test Strength for Card/Unit section. QKPLOT, or "Quick Plot" is a computer subroutine available in the IBM 370 Scientific Subprogram Library. A user can implement it by making a call to QKPLOT while providing the necessary points to be plotted. A logarithmic X (time) and linear Y = F(X) (test strength) set of axes was chosen and more than a thousand points were plotted. This program can be accessed using FORTRAN IV language.

A. 3 Multiple Linear Regression (MLRG): Least Squares Fit and Analysis

Regression analyses were performed in the sections on Computation of Test Strength for Equipment/System Level and Conversion of MTBF to Defects, in which the computer program, MLRG, was used. MLRG, is a subroutine available in the IBM 370 Scientific Subprogram Library. A call to this routine with a set of observations of dependent and independent variables will cause it to compute the coefficients of a multiple linear equation expressing the dependent variable as a function of the independent ones. MLRG also calculates a set of statistical quantities such as the coefficient of multiple determination which provides a measure of the least-squares fit. This program can be accessed using the FORTRAN IV language.

A. 4 Least Squares Curve Fit (CURFIT)

In the sections on Conversion of MTBF to Defects and Determining Relationship of Test Strength to Number of Subcontractors and Percent Non-Standard Parts, the computer program, CURFIT was used for the regression analysis. This program is available on the Dartmouth Time Sharing System (DTSS) and is written in the BASIC language. Using the input data values for the independent and dependent variables, the routine fits them to six different curve types, with output information of the measure of fit and the equation coefficients. The six curves used are:

(1) $Y = A + BX$, linear

(2) $Y = Ae^{BX}$, exponential

(3) $Y = AX^B$, power

(4) $Y = A + B/X$, hyperbolic

(5) $Y = 1/(A + BX)$, hyperbolic

(6) $Y = X/(A + BX)$, hyperbolic

A.5 SDO Computer Program Printout

```
      INTEGER T
      INTEGER*2 TV(20,300),SEQ(20,300),TV1(17000),SEQ1(17000)
      DIMENSION N(5),ADEF(5),F(11,4,5),R1(11,4,5),R2(11,4,5),CT(5,5),
     +CR1(5,5),CR2(5,5),TS(20,300),TC(20,300),N1(20),NF(20),
     +P(11,4,5),TS1(17000),TC1(17000),SCOST(5,5),IARRAY(20),
     +PARRAY(11,4,5)
      DATA NF,TS,TC,TS1,TC1/20*0,46000*0./
      DATA PARRAY/220*1.0/
      DATA P,F,R1,R2/880*1.0/
      DATA N/5*5/
      CALL DATA (NCYC,M,PDEF,CREQD,E,ITV,N,ADEF,
     +P,F,R1,R2,CR1,CR2,FRF,FRM,LEVEL,ITYP,
     +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
     +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
     +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
      LL=0
      ADIN=0.0
      DO 1 I=1,M
    1 ADIN=ADIN+ADEF(I)
      DIN=ADIN+PDEF
      IF(FRF.EQ.0.0) GO TO 5
      OPTS=0.0
      OPTS2=0.0
      HOURS2=0.0
      DO 220 I=1,3
      GO TO (201,202,203),I
  201 I2=2
      GO TO 210
  202 I2=3
      GO TO 210
  203 I2=5
  210 CONTINUE
      READ(13,*,END=220) PMAX,CYCMAX
      IF (PMAX.EQ.0.0.OR.CYCMAX.EQ.0.0) GO TO 220
      CALL SSPROB(ITV,ITV,ITV,ITV,M,I2,PARRAY,1,CT,0.,0.,ITV,
     +HOURS,AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,
     +PMAX,AMIN23,CYCMAX,AMIN24,AMAX31,AMIN31,PMAX,AMIN32,AMAX33,
     +AMIN33,CYCMAX,AMIN34,AMAX41,AMIN41,PMAX,AMIN51,CYCMAX,AMIN52)
      OPTS1=PARRAY(1,M,I2)
      OPTS=OPTS2+OPTS1*(1.0-OPTS2)
      OPTS2=OPTS1
      HOURS1=HOURS
      HOURST=AMAX1(HOURS1,HOURS2)
```

```
      HOURS2=HOURST
      PARRAY(1,M,I2)=1.0
  220 CONTINUE
      GO TO 240
  230 OPTS=1.0
      HOURST=26280.
  240 IF (OPTS.EQ.0.0) GO TO 230
      DREQD=HOURST*((10.**(-6))*(FRF-FRM))/OPTS
      SREQD=1.0-DREQD/DIN
      WRITE(6,*) HOURST,SREQD
    5 DO 50 I1=1,M
      NI1=N(I1)
      DO 52 I2=1,NI1
      LL=LL+1
      MV=0
      READ(10,*,END=7) A1,B1
      GO TO 8
    7 A1=0.0
      B1=0.0
    8 DO 103 KK4=1,ITV
      DO 103 KK3=1,ITV
      DO 102 KK2=1,ITV
      DO 101 KK1=1,ITV
      MV=MV+1
      DO 10 I=1,NCYC
   10 PARRAY(I,I1,I2)=P(I,I1,I2)
      CALL SSPROB(KK1,KK2,KK3,KK4,I1,I2,PARRAY,NCYC,CT,A1,B1,ITV,HOURS,
     +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
     +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
     +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
      CALL SCREEN(NCYC,M,N,PDEF,DIN,ADEF,PARRAY,F,R1,R2,CT,CR1,CR2,SS,
     +TCOST,I1,I2,SCOST,TCMIN,0.0)
      TS(LL,MV)=SS
      TC(LL,MV)=TCOST
  101 CONTINUE
      IF(I2-4) 102,104,102
  102 CONTINUE
      IF((I2-1)*(I2-5)) 103,104,103
  103 CONTINUE
  104 CONTINUE
      DO 12 I=1,NCYC
   12 PARRAY(I,I1,I2)=1.0
      N1(LL)=MV
      IF(LL-2) 52,15,20
   15 K1=N1(LL-1)
      GO TO 30
   20 K1=K
   30 K2=N1(LL)
      NSEQ=K1*K2
      DO 40 J1=1,K1
      DO 40 J2=1,K2
      U=TS(LL,J2)*(1.0-TS(LL-1,J1))+TS(LL-1,J1)
```

```
      V=TC(LL-1,J1)+(1.-TS(LL-1,J1))*TS(LL,J2)*TC(LL,J2)
   36 NF(LL)=NF(LL)+1
      JJ=NF(LL)
      SEQ1(JJ)=J1
      TV1(JJ)=J2
      TS1(JJ)=U
      TC1(JJ)=V
   40 CONTINUE
      CALL RANK(TS1,TC1,NSEQ,SEQ1,TV1)
      QC=0.0
      QS=0.0
      K=0
      DO 51 I=1,NSEQ
      IF((TS1(I).EQ.0.0).OR.(TC1(I).EQ.0.0)) GO TO 51
      IF((TS1(I)-QS)/TS1(I).LT.E) GO TO 51
      IF((TC1(I)-QC)/TC1(I).LT.E) GO TO 51
      QC=TC1(I)
      QS=TS1(I)
      K=K+1
      TC(LL,K)=TC1(I)
      TS(LL,K)=TS1(I)
      SEQ(LL,K)=SEQ1(I)
      TV(LL,K)=TV1(I)
      TC1(I)=0.
      TS1(I)=0.
      SEQ1(I)=0
      TV1(I)=0
   51 CONTINUE
   52 CONTINUE
   50 CONTINUE
      CALL SEARCH(LL,K,CREQD,SREQD,SEQ,TV,TC,TS,IARRAY,TCMIN,TSMAX,DIN)
      CALL REPORT(M,NCYC,N,PDEF,DIN,ADEF,P,F,R1,R2,CT,CR1,CR2,IARRAY,
     +A1,B1,ITV,TCMIN,TSMAX,
     +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
     +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
     +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
      DEBUG SUBCHK
      END
      SUBROUTINE SCREEN(NCYC,M,N,PDEF,DIN,ADEF,P,F,R1,R2,CT,CR1,CR2,
     +SS,TCOST,I1,I2,SCOST,TCMIN,FLAG)
      DIMENSION X(11,4,5),P(11,4,5),F(11,4,5),R1(11,4,5),Q(20),
     +R2(11,4,5),
     +TCOSTL(5,5),COSTL(5),N(5),CT(5,5),CR1(5,5),ADEF(5),
     +CR2(5,5),SCOST(5,5)
      DO 10 I=1,NCYC
      DO 10 J=1,M
      NJ=N(J)
      DO 10 K=1,NJ
   10 X(I,J,K)=0.0
      X(1,1,1)=ADEF(1)+PDEF
      DO 35 J=1,M
      NJ=N(J)
```

```
      DO 35 K=1,NJ
      IF(K-1) 20,20,32
   20 IF(J-1) 35,35,31
   31 X(1,J,K)=P(1,J-1,N(J-1))*X(1,J-1,N(J-1))+ADEF(J)
      GO TO 35
   32 X(1,J,K)=P(1,J,K-1)*X(1,J,K-1)
   35 CONTINUE
      SUMX=0.
      DO 95 I=1,NCYC
      X(I+1,1,1)=0.0
   50 DO 51 J=1,M
      NJ=N(J)
      DO 51 K=1,NJ
   51 X(I+1,1,1)=X(I+1,1,1)+(1-P(I,J,K))*F(I,J,K)*(1-R1(I,J,K))*X(I,J,K)
      DO 94 J=1,M
      NJ=N(J)
      DO 94 K=1,NJ
      IF(X(I,J,K).LT.1.0) GO TO 94
      IF(J.EQ.1.AND.K.EQ.1) GO TO 94
      IF(J.GT.1.AND.K.EQ.1) GO TO 90
      IF(J.GE.1.AND.K.GT.1) GO TO 80
      GO TO 94
   90 X(I+1,J,1)=P(I+1,J-1,N(J-1))*X(I+1,J-1,N(J-1))+
     +(1-P(I,J,1))*(1-F(I,J,1))*(1-R2(I,J,1))*X(I,J,1)
      GO TO 94
   80 X(I+1,J,K)=P(I+1,J,K-1)*X(I+1,J,K-1)+(1-P(I,J,K))*(1-F(I,J,K))*
     *(1-R2(I,J,K))*X(I,J,K)
   94 CONTINUE
   95 CONTINUE
      SUM=0.0
      DO 110 I=1,NCYC
      NM=N(M)
      SUM=SUM+X(I,M,NM)*P(I,M,NM)
  110 CONTINUE
      DOUT=SUM
      SS=1.0-DOUT/DIN
      DELTA=DIN-DOUT
      ACOST=0.0
      TCOST=0.0
      DO 120 J=1,M
      DO 120 K=1,5
  120 SCOST(J,K)=0.0
      IF(FLAG.NE.0.0) GO TO 126
      DO 200 I=1,NCYC
      CR=CR1(I1,I2)*F(I,I1,I2)+CR2(I1,I2)*(1.0-F(I,I1,I2))
      COST=CT(I1,I2)+CR*(1.0-P(I,I1,I2))*X(I,I1,I2)
  200 ACOST=ACOST+COST
      GO TO 205
  126 DO 160 J=1,M
      DO 160 K=1,5
      SUMTS1=0 0
      SUMTS2=0.0
      DO 130 I=1,NCYC
```

```
      SUMTS1=SUMTS1+(1.-P(I,J,K))*X(I,J,K)
  130 SUMTS2=SUMTS2+X(I,J,K)
      SCOST(J,K)=SUMTS1/SUMTS2
  160 TCOST=TCOST+SCOST(J,K)
      SUMTC=0.0
      DO 140 J=1,M
      DO 140 K=1,5
      SCOST(J,K)=SCOST(J,K)*(TCMIN/TCOST)
  140 SUMTC=SUMTC+SCOST(J,K)
      TCOST=SUMTC
      GO TO 300
  205 IF(DIN-DOUT) 210,210,220
  210 DELTA=1.0
  220 TCOST=ACOST/DELTA
  300 RETURN
      DEBUG SUBCHK
      END
      SUBROUTINE RANK(TS1,TC1,NSEQ,SEQ1,TV1)
      INTEGER*2 TV1(17000),SEQ1(17000)
      DIMENSION TS1(17000),TC1(17000)
      N2=NSEQ
      M1=N2
  650 M1=INT(M1/2.)
      IF(M1.EQ.0) GO TO 830
      H1=N2-M1
      J=1
  690 I=J
  700 L1=I+M1
      IF(TC1(I).LE.TC1(L1)) GO TO 800
      A1=TC1(I)
      B1=TS1(I)
      A2=SEQ1(I)
      B2=TV1(I)
      TC1(I)=TC1(L1)
      TS1(I)=TS1(L1)
      SEQ1(I)=SEQ1(L1)
      TV1(I)=TV1(L1)
      TC1(L1)=A1
      TS1(L1)=B1
      SEQ1(L1)=A2
      TV1(L1)=B2
      I=I-M1
      IF(I.GE.1) GO TO 700
  800 J=J+1
      IF(J.LE.H1) GO TO 690
      GO TO 650
      DEBUG SUBCHK
  830 RETURN
      END
      SUBROUTINE SEARCH(LL,N0,CREQD,SREQD,SEQ,TV,TC,TS,IARRAY,TCMIN,
     +TSMAX,DIN)
      INTEGER T,S,S1,S2
      INTEGER*2 TV(20,300),SEQ(20,300)
```

```
      DIMENSION TC(20,300),TS(20,300),IARRAY(20)
      DO 1 I=1,NO
      TCTOT=TC(LL,I)*DIN*TS(LL,I)
    1 TC(LL,I)=TCTOT
      IF(CREQD) 5,5,10
    5 IF(SREQD) 400,400,15
   10 K=NO
    7 IF(TC(LL,K)-CREQD) 20,20,25
   15 K=1
   17 IF(TS(LL,K)-SREQD) 30,20,20
   20 S1=SEQ(LL,K)
      T=TV(LL,K)
      IARRAY(LL)=T
      TCMIN=TC(LL,K)
      TSMAX=TS(LL,K)
      K=1
      GO TO 40
   25 K=K-1
      IF(K) 200,200,7
   30 K=K+1
      IF(K-NO) 17,17,200
   40 I=LL-1
   45 IF(I-1) 300,300,100
  100 S=SEQ(I,S1)
      T=TV(I,S1)
      S2=S1
      S1=S
      IARRAY(I)=T
      I=I-1
      GO TO 45
  200 WRITE(6,201)
  201 FORMAT(/1X,'REQUIREMENT CANNOT BE MET')
      STOP
  300 IARRAY(1)=S
  400 CONTINUE
       DEBUG SUBCHK
      RETURN
      END
      SUBROUTINE SSPROB(K1,K2,K3,K4,I1,I2,P,NCYC,CT,A1,B1,ITV,HOURS,
     +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
     +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
     +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
      DIMENSION P(11,4,5),CT(5,5)
      GO TO (10,20,30,40,50),I2
   10 CONTINUE
C  TEST ONE:  CONSTANT TEMPERATURE(CT)
      E1=EXP(.0122*(((AMAX11-AMIN11)*K1+AMIN11*ITV-AMAX11)/(ITV-1.)+
     +273.0))
      E2=EXP(-((AMAX12-AMIN12)*K2+AMIN12*ITV-AMAX12)*.0000263*E1/
     +(ITV-1.))
      PFT=.6*(1.0-E2)
      SS=1.0-PFT
      HOURS=((AMAX12-AMIN12)*K2+AMIN12*ITV-AMAX12)/(ITV-1.)
```

```
      IF(B1) 11,11,105
   11 GO TO(101,102,103,104),I1
  101 CT(1,I2)=(0.15)*HOURS
      GO TO 60
  102 CT(2,I2)=(0.15)*HOURS
      GO TO 60
  103 CT(3,I2)=HOURS
      GO TO 60
  104 CT(4,I2)=HOURS
      GO TO 60
   20 CONTINUE
C  TEST TWO:  CYCLED TEMPERATURE(CYT)
      TE=((ABS(((AMAX21-AMIN21)*K1+AMIN21*ITV-AMAX21)/(ITV-1.)-25.)+
     +ABS(((AMAX22-AMIN22)*K2+AMIN22*ITV-AMAX22)/(ITV-1.)-25.0))+
     +50.0)/2.0
      E1=EXP(.0122*(TE+273.0))
      TT=((AMAX23-AMIN23)*K3+AMIN23*ITV-AMAX23)*4.5/(ITV-1.)
      E2=EXP(-((AMAX24-AMIN24)*K4+AMIN24*ITV-AMAX24)*TT*.0000263*E1/
     +(ITV-1.))
      PFDT=.8*(1.0-E2)
      IF ((AMAX21-AMIN21)*K1+AMIN21*ITV-AMAX21.EQ.(AMAX22
     +-AMIN22)*K2+AMIN22*ITV-AMAX22) PFDT=0.
      SS=1.0-PFDT
      IF((AMAX23-AMIN23)*K3+AMIN23*ITV-AMAX23) 5,5,7
    7 HOURS=((AMAX21-AMIN21)*K1+AMIN21*ITV-AMAX21+(AMAX22-AMIN22)*K2+
     +AMIN22*ITV-AMAX22)*((AMAX24-AMIN24)*K4+AMIN24*ITV-AMAX24)/
     +(60.*((AMAX23-AMIN23)*K3+AMIN23*ITV-AMAX23)*(ITV-1.))
      GO TO 8
    5 HOURS=0.
    8 IF(B1)21,21,105
   21 GO TO(201,202,203,204),I1
  201 CT(1,I2)=(0.15)*HOURS
      GO TO 60
  202 CT(2,I2)=(0.15)*HOURS
      GO TO 60
  203 CT(3,I2)=HOURS
      GO TO 60
  204 CT(4,I2)=HOURS
      GO TO 60
   30 CONTINUE
C  TEST THREE:  VIBRATION(VIB)
      TE=ABS(((AMAX33-AMIN33)*K3+AMIN33*ITV-AMAX33)/(ITV-1.))+25.0
      E1=EXP(.0122*(TE+273.0))
      E2=EXP(-(.0000789*((AMAX31-AMIN31)*K1+AMIN31*ITV-AMAX31)*((AMAX32-
     +AMIN32)*K2+AMIN32*ITV-AMAX32)*((AMAX34-AMIN34)*K4+AMIN34*ITV-
     +AMAX34)*E1)/(ITV-1.)**3)
      PFV=.2*(1.0-E2)
      SS=1.0-PFV
      HOURS=((AMAX32-AMIN32)*K2+AMIN32*ITV-AMAX32)*((AMAX34-AMIN34)*K4+
     +AMIN34*ITV-AMAX34)/(60.*(ITV-1.)**2)
      IF(B1) 31,31,105
   31 GO TO(301,302,303,304),I1
  301 CT(1,I2)=(0.15)*HOURS
```

```
      GO TO 60
  302 CT(2,I2)=(0.15)*HOURS
      GO TO 60
  303 CT(3,I2)=HOURS
      GO TO 60
  304 CT(4,I2)=HOURS
      GO TO 60
   40 CONTINUE
C   TEST FOUR:  CONSTANT POWER(CP)
      HOURS=((AMAX41-AMIN41)*K1+AMIN41*ITV-AMAX41)/(ITV-1.)
      IF(I1.GT.2) GO TO 41
C    CARD/MODULE LEVELS
      PWR=664.965/(((AMAX41-AMIN41)*K1+AMIN41*ITV-AMAX41)/(ITV-1.)+
     +664.965)
      SS=PWR
      IF(B1) 42,42,105
   42 GO TO(401,402),I1
  401 CT(1,I2)=(0.15)*HOURS
      GO TO 60
  402 CT(2,I2)=(0.15)*HOURS
      GO TO 60
   41 CONTINUE
C    EQUIPMENT/SYSTEM LEVELS
      PWR=3049.875/(((AMAX41-AMIN41)*K1+AMIN41*ITV-AMAX41)/(ITV-1.)+
     +3049.875)
      SS=PWR
      IF(B1) 43,43,105
   43 GO TO(403,404,403,404),I1
  403 CT(3,I2)=HOURS
      GO TO 60
  404 CT(4,I2)=HOURS
      GO TO 60
   50 CONTINUE
C   TEST FIVE:  CYCLED POWER(CYP)
      HOURS=((AMAX51-AMIN51)*K1+AMIN51*ITV-AMAX51)*((AMAX52-AMIN52)*K2+
     +AMIN52*ITV-AMAX52)/(ITV-1.)**2
      IF(I1.GT.2) GO TO 51
C    CARD/MODULE LEVELS
      R1=664.965/(((AMAX51-AMIN51)*K1+AMIN51*ITV-AMAX51)/(ITV-1.)+
     +664.965)
      PWRC=R1**(((AMAX52-AMIN52)*K2+AMIN52*ITV-AMAX52)/(ITV-1.))
      SS=PWRC
      IF(B1) 52,52,105
   52 GO TO(501,502),I1
  501 CT(1,I2)=(0.15)*HOURS
      GO TO 60
  502 CT(2,I2)=(0.15)*HOURS
      GO TO 60
   51 CONTINUE
C    EQUIPMENT/SYSTEM LEVELS
      R1=3049.875/(((AMAX51-AMIN51)*K1+AMIN51*ITV-AMAX51)/(ITV-1.)+
     +3049.875)
      PWRC=R1**(((AMAX52-AMIN52)*K2+AMIN52*ITV-AMAX52)/(ITV-1.))
```

```
      SS=PWRC
      IF(B1) 53,53,105
   53 GO TO(503,504,503,504),I1
  503 CT(3,I2)=HOURS
      GO TO 60
  504 CT(4,I2)=HOURS
      GO TO 60
  105 CT(I1,I2)=B1*HOURS+A1
   60 CONTINUE
      DO 70 I=1,NCYC
      D=1.0-(1.0-SS)*P(I,I1,I2)
   70 P(I,I1,I2)=D
      D_BUG SUBCHK
      RETURN
      END
      SUBROUTINE REPORT(M,NCYC,N,PDEF,DIN,ADEF,P,F,R1,R2,CT,CR1,CR2,
     +IARRAY,A1,B1,ITV,TCMIN,TSMAX,
     +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
     +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
     +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
      REAL LCOST(5)
      DIMENSION NP(5,5,5),N(5),P(11,4,5),F(11,4,5),
     +R1(11,4,5),R2(11,4,5),CR1(5,5),CR2(5,5),CT(5,5),SCOST(5,5),
     +TEST(5),IR(5),IARRAY(20),ANP(5,5,5),ADEF(5)
      REWIND 10
      DATA NP/125*1/
      DATA LCOST/5*0./
      DATA TEST/'CT  ','CYT ','VIB ','CP  ','CYP '/
      DATA ANP/125*0./
      I=0
      DO 65 I1=1,M
      DO 65 I2=1,5
      READ(10,*) A1,B1
      I=I+1
      IR(1)=IARRAY(I)
      GO TO (30,50,50,20,30),I2
   20 NP(I1,I2,1)=IARRAY(I)
      GO TO 60
   30 DO 33 K=2,3
      IR(K)=MOD(IR(K-1),ITV**(3-K))
      IF(IR(K-1)) 32,32,31
   31 NP(I1,I2,4-K)=INT(FLOAT(IR(K-1))/(FLOAT(ITV))**(3-K)+.999999)
      GO TO 33
   32 NP(I1,I2,4-K)=ITV
   33 CONTINUE
      GO TO 60
   40 DO 43 K=2,4
      IR(K)=MOD(IR(K-1),ITV**(4-K))
      IF(IR(K-1)) 42,42,41
   41 NP(I1,I2,5-K)=INT(FLOAT(IR(K-1))/(FLOAT(ITV))**(4-K)+.999999)
      GO TO 43
   42 NP(I1,I2,5-K)=ITV
   43 CONTINUE
```

```
      GO TO 60
   50 DO 53 K=2,5
      IR(K)=MOD(IR(K-1),ITV**(5-K))
      IF(IR(K-1)) 52,52,51
   51 NP(I1,I2,6-K)=INT(FLOAT(IR(K-1))/(FLOAT(ITV))**(5-K)+.999999)
      GO TO 53
   52 NP(I1,I2,6-K)=ITV
   53 CONTINUE
      GO TO 60
   60 CALL SSPROB(NP(I1,I2,1),NP(I1,I2,2),NP(I1,I2,3),NP(I1,I2,4),I1,I2,
     +P,NCYC,CT,A1,B1,ITV,HOURS,
     +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
     +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
     +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
   65 CONTINUE
      CALL SCREEN(NCYC,M,N,FDEF,DIN,ADEF,P,F,R1,R2,CT,CR1,CR2,
     +SS,FCOST,I1,I2,SCOST,TCMIN,1.0)
      DO 70 I1=1,M
      DO 70 I2=1,5
   70 LCOST(I1)=LCOST(I1)+SCOST(I1,I2)
      IQ=0
      WRITE(6,100)
      DO 90 I1=1,M
      DO 90 I2=1,5
      ANP(I1,4,1)=((AMAX41-AMIN41)*NP(I1,4,1)+AMIN41*ITV-AMAX41)/
     +(ITV-1.)
      ANP(I1,1,1)=((AMAX11-AMIN11)*NP(I1,1,1)+AMIN11*ITV-AMAX11)/
     +(ITV-1.)
      ANP(I1,1,2)=((AMAX12-AMIN12)*NP(I1,1,2)+AMIN12*ITV-AMAX12)/
     +(ITV-1.)
      ANP(I1,5,1)=((AMAX51-AMIN51)*NP(I1,5,1)+AMIN51*ITV-AMAX51)/
     +(ITV-1.)
      ANP(I1,5,2)=((AMAX52-AMIN52)*NP(I1,5,2)+AMIN52*ITV-AMAX52)/
     +(ITV-1.)
      ANP(I1,2,1)=((AMAX21-AMIN21)*NP(I1,2,1)+AMIN21*ITV-AMAX21)/
     +(ITV-1.)
      ANP(I1,2,2)=((AMAX22-AMIN22)*NP(I1,2,2)+AMIN22*ITV-AMAX22)/
     +(ITV-1.)
      ANP(I1,2,3)=((AMAX23-AMIN23)*NP(I1,2,3)+AMIN23*ITV-AMAX23)/
     +(ITV-1.)
      ANP(I1,2,4)=((AMAX24-AMIN24)*NP(I1,2,4)+AMIN24*ITV-AMAX24)/
     +(ITV-1.)
      ANP(I1,3,1)=((AMAX31-AMIN31)*NP(I1,3,1)+AMIN31*ITV-AMAX31)/
     +(ITV-1.)
      ANP(I1,3,2)=((AMAX32-AMIN32)*NP(I1,3,2)+AMIN32*ITV-AMAX32)/
     +(ITV-1.)
      ANP(I1,3,3)=((AMAX33-AMIN33)*NP(I1,3,3)+AMIN33*ITV-AMAX33)/
     +(ITV-1.)
      ANP(I1,3,4)=((AMAX34-AMIN34)*NP(I1,3,4)+AMIN34*ITV-AMAX34)/
     +(ITV-1.)
      GO TO (101,102,103,104,105),I2
  101 IF(NP(I1,1,2).EQ.1) GO TO 76
      GO TO 106
```

```
102 IF(NP(I1,2,3).EQ.1) GO TO 76
    GO TO 106
103 IF(NP(I1,3,2).EQ.1) GO TO 76
    GO TO 106
104 IF(NP(I1,4,1).EQ.1) GO TO 76
    GO TO 106
105 IF(NP(I1,5,1).EQ.1) GO TO 76
    GO TO 106
 76 DO 77 K=1,4
 77 ANP(I1,I2,K)=0.
106 IF(I1-IQ) 80,80,75
 75 WRITE(6,110) I1,LCOST(I1)
 80 WRITE(6,120) I2,TEST(I2),(ANP(I1,I2,K),K=1,4),SCOST(I1,I2)
 90 IQ=I1
    WRITE(6,130) FCOST
100 FORMAT('1',28X,'T E S T   D E S C R I P T I O N'/
   +39X,'PARAMETER VALUE'/10X,'TEST SEQUENCE',5X,'TYPE',2X,
   +'NO. 1',2X,'NO. 2',2X,'NO. 3',2X,'NO. 4',2X,'TOTAL COST'/
   +7X,66('_')//)
110 FORMAT(' ',8X,'LEVEL',2X,'NO. ',I2,39X,F12.2)
120 FORMAT(' ',12X,'TEST  NO. ',I2,3X,A4,1X,4F7.2,F12.2)
130 FORMAT(' ',7X,66('_')//' ',8X,'TOTAL',' COST',43X,F12.2//' ',
   +61X,12('_')/' ',61X,12('_'))
    WRITE(6,140) TSMAX
140 FORMAT(' ',8X,'TOTAL SEQUENCE TEST STRENGTH=',F8.6)
    DEBUG SUBCHK
    RETURN
    END
    SUBROUTINE DATA (NCYC,M,PDEF,CREQD,E,ITV,N,ADEF,
   +P,F,R1,R2,CR1,CR2,FRF,FRM,LEVEL,ITYP,
   +AMAX11,AMIN11,AMAX12,AMIN12,AMAX21,AMIN21,AMAX22,AMIN22,AMAX23,
   +AMIN23,AMAX24,AMIN24,AMAX31,AMIN31,AMAX32,AMIN32,AMAX33,AMIN33,
   +AMAX34,AMIN34,AMAX41,AMIN41,AMAX51,AMIN51,AMAX52,AMIN52)
    DIMENSION N(5),ADEF(5),P(11,4,5),
   +F(11,4,5),R1(11,4,5),R2(11,4,5),CR1(5,5),CR2(5,5)
    READ(4,*) NCYC,M,NPARTS,CREQD,E,ITV,FRF,FRM
    READ(4,*,END=2) PDEF
    IF(PDEF) 2,2,1
  2 PDEF=0.01*NPARTS
    GO TO 3
  1 PDEF=PDEF*NPARTS
  3 DO 5 I=1,M
    READ(4,*,END=4) ADEF(I)
    IF(ADEF(I)) 4,4,5
  4 ADEF(I)=(7./(3.*M))*PDEF
    GO TO 7
  5 ADEF(I)=ADEF(I)*NPARTS
  7 WRITE(6,98)
    WRITE(6,90) NCYC,M,PDEF,CREQD,E,ITV,FRF,FRM
    WRITE(6,99)
    WRITE(6,91) (I,N(I),ADEF(I),I=1,M)
    DO 30 I1=1,M
    DO 30 I2=1,5
```

```
      READ(11,*,END=10) P(1,I1,I2)
      IF (P(1,I1,I2))  10,10,20
   10 DO 15 I=1,NCYC
   15 P(I,I1,I2)=.75
      GO TO 30
   20 DO 25 I=1,NCYC
   25 P(I,I1,I2)=P(1,I1,I2)
   30 CONTINUE
      WRITE(6,92)
      WRITE(6,*) ((P(1,J,K),K=1,5),J=1,M)
      DO 40 I1=1,M
      DO 40 I2=1,5
      READ(8,*,END=45) F(1,I1,I2)
      IF (F(1,I1,I2))  45,45,47
   45 DO 46 I=1,NCYC
      F(I,1,I2)=1.0
      F(I,2,I2)=0.23
      F(I,3,I2)=0.43
   46 F(I,4,I2)=0.65
      GO TO 40
   47 DO 48 I=1,NCYC
   48 F(I,I1,I2)=F(1,I1,I2)
   40 CONTINUE
      WRITE(6,93)
      WRITE(6,*) ((F(1,J,K),K=1,5),J=1,M)
      DO 80 I1=1,M
      DO 80 I2=1,5
      READ(9,*,END=55)  R1(1,I1,I2),R2(1,I1,I2)
      IF (R1(1,I1,I2)) 55,55,60
   55 DO 56 I=1,NCYC
   56 R1(I I1,I2)=0.5
      GO TO 61
   60 DO 57 I=1,NCYC
   57 R1(I,I1,I2)=R1(1,I1,I2)
   61 IF (R2(1,I1,I2)) 65,65,70
   65 DO 66 I=1,NCYC
   66 R2(I,I1,I2)=0.5
      GO TO 80
   70 DO 67 I=1,NCYC
   67 R2(I,I1,I2)=R2(1,I1,I2)
   80 CONTINUE
      WRITE(6,94)
      WRITE(6,*) ((R1(1,J,K),K=1,5),J=1,M)
      WRITE(6,95)
      WRITE(6,*) ((R2(1,J,K),K=1,5),J=1,M)
      DO 300 I1=1,M
      DO 300 I2=1,5
      READ(4,*,END=100) B2,B3
      IF (B2) 100,100,105
  100 GO TO (101,102,103,104),I1
  101 CR1(1,I2)=9.5
      GO TO 150
  102 CR1(2,I2)=9.46
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```
      GO TO 150
  103 CR1(3,I2)=51.5
      GO TO 150
  104 CR1(4,I2)=63.0
      GO TO 150
  105 CR1(I1,I2)=B2
  150 IF (B3) 200,200,110
  200 GO TO (201,202,203,204),I1
  201 CR2(1,I2)=0.1
      GO TO 300
  202 CR2(2,I2)=3.67
      GO TO 300
  203 CR2(3,I2)=45.5
      GO TO 300
  204 CR2(4,I2)=57.0
      GO TO 300
  110 CR2(I1,I2)=B3
  300 CONTINUE
      WRITE(6,96)
      WRITE(6,*) ((CR1(J,K),K=1,5),J=1,M)
      WRITE(6,97)
      WRITE(6,*) ((CR2(J,K),K=1,5),J=1,M)
      DO 89 I=1,NCYC
      DO 89 J=1,M
      NJ=N(J)
      DO 89 K=1,NJ
      F(I,J,K)=F(1,J,K)
      R1(I,J,K)=R1(1,J,K)
   89 R2(I,J,K)=R2(1,J,K)
C  TEST ONE:  CONSTANT TEMPERATURE
      READ(12,*) AMAX11,AMIN11
      IF(AMAX11.NE.0..OR.AMIN11.NE.0.) GO TO 1001
      AMAX11=70.
      AMIN11=-55.
 1001 READ(12,*) AMAX12,AMIN12
      IF(AMAX12.NE.0..OR.AMIN12.NE.0.) GO TO 1002
      AMAX12=170.
      AMIN12=0.
 1002 CONTINUE
C  TEST TWO:  CYCLED TEMPERATURE
      READ(12,*) AMAX21,AMIN21
      IF(AMAX21.NE.0..OR.AMIN21.NE.0.) GO TO 2001
      AMAX21=70.
      AMIN21=25.
 2001 READ(12,*) AMAX22,AMIN22
      IF(AMAX22.NE.0..OR.AMIN22.NE.0.) GO TO 2002
      AMAX22=-50.
      AMIN22=-25.
 2002 READ(12,*) AMAX23,AMIN23
      IF(AMAX23.NE.0..OR.AMIN23.NE.0.) GO TO 2003
      AMAX23=10.
      AMIN23=0.
 2003 READ(12,*) AMAX24,AMIN24
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      IF(AMAX24.NE.0..OR.AMIN24.NE.0.) GO TO 2004
      AMAX24=64.
      AMIN24=10.
 2004 CONTINUE
C  TEST THREE:  VIBRATION
      READ(12,*) AMAX31,AMIN31
      IF(AMAX31.NE.0..OR.AMIN31.NE.0.) GO TO 3001
      AMAX31=6.
      AMIN31=1.
 3001 READ(12,*) AMAX32,AMIN32
      IF(AMAX32.NE.0..OR.AMIN32.NE.0.) GO TO 3002
      AMAX32=2.
      AMIN32=0.
 3002 READ(12,*) AMAX33,AMIN33
      IF(AMAX33.NE.0..OR.AMIN33.NE.0.) GO TO 3003
      AMAX33=25.
      AMIN33=25.
 3003 READ(12,*) AMAX34,AMIN34
      IF(AMAX34.NE.0..OR.AMIN34.NE.0.) GO TO 3004
      AMAX34=64.
      AMIN34=10.
 3004 CONTINUE
C  TEST FOUR:  CONSTANT POWER
      READ(12,*) AMAX41,AMIN41
      IF(AMAX41.NE.0..OR.AMIN41.NE.0.) GO TO 4001
      AMAX41=168.
      AMIN41=0.
 4001 CONTINUE
C  TEST FIVE:  CYCLED POWER
      READ(12,*) AMAX51,AMIN51
      IF(AMAX51.NE.0..OR.AMIN51.NE.0.) GO TO 5001
      AMAX51=8.
      AMIN51=0.
 5001 READ(12,*) AMAX52,AMIN52
      IF(AMAX52.NE.0..OR.AMIN52.NE.0.) GO TO 5002
      AMAX52=168.
      AMIN52=3.
 5002 CONTINUE
   98 FORMAT('1',28X,'TABLE A - PROGRAM DATA'/' ',80('_')/' ',
     +4X,'NCYC',11X,'M',6X,'(PDEF.NPARTS)',4X,'CREQD',10X,
     +'E',11X,'ITV',10X,'FRF',10X,'FRM'/' ',
     +130('-')//)
   99 FORMAT('1',24X,'TABLE B - TEST AND ASSEMBLY DATA'/' ',80('_')/' ',
     +4X,'ASSEMBLY LEVEL',2X,'NUMBER OF SCREENS',2X,
     +'EXPECTED NUMBER OF ASSEMBLY DEFECTS'/' ',4X,14('_'),2X,17('_'),2X
     +,35('_')//)
   90 FORMAT(' ',5X,I2,12X,I1,6X,F13.0,F13.2,5X,F8.6,5X,I3,5X,2F13.2)
   91 FORMAT(' ',7X,I2,14X,I2,22X,F9.0)
   92 FORMAT('1',14X,'TABLE C - DETECTION PROBABILITIES FOR TEST',
     +' EQUIPMENT'/' ',80('_')//)
   93 FORMAT('1',4X,'TABLE D - FRACTION OF DEFECTS REQUIRING ',
     +'PRIMARY LEVEL (CARD ASSY) REWORK'/' ',80('_')//)
   94 FORMAT('1',20X,'TABLE E-FRACTION OF DEFECTS REMOVED AT'/' ',
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     +19X,'THE PRIMARY LEVEL PER REWORK/RETEST CYCLE'
     +/' ',80('_')//)
  95 FORMAT('1',14X,'TABLE F - FRACTION OF DEFECTS REMOVED AT ',
     +'THE HIGHER'/' ',20X,'ASSEMBLY LEVEL PER REWORK/',
     +'RETEST CYCLE'/' ',80('_')//)
  96 FORMAT('1',18X,'TABLE G - PRIMARY LEVEL REWORK COST PER',
     +' CYCLE'/' ',80('_')//)
  97 FORMAT('1',13X,'TABLE H - HIGHER ASSEMBLY LEVEL REWORK ',
     +'COST PER CYCLE'/' ',80('_')//)
      RETURN
      END
```