Research and Development Technical Report

ECOM - 4487

COST OPTIMIZING SYSTEM TO EVALUATE RELIABILITY (COSTER)

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April 1977

ECOM

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER ECOM-4487	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) COST OPTIMIZING SYSTEM TO EVALUATE RELIABILITY (COSTER).		5. TYPE OF REPORT & PERIOD COVERED (9) Technical Report. Jan[redacted]75-Dec[redacted]76
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) John P. Solomond, Grace A. Marseglia		8. CONTRACT OR GRANT NUMBER(s) (14) ECOM-4487
9. PERFORMING ORGANIZATION NAME AND ADDRESS Advanced Methodology Branch, Reliab, Maint and HFE Division, Product Assurance Directorate, US Army Electronics Command, Fort Monmouth, NJ		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 5799.00.00.1J0.0000 TCEZZ7
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Electronics Command, ATTN: DRSEL-PA-RAM, Fort Monmouth, NJ 07703		12. REPORT DATE April 1977
		13. NUMBER OF PAGES 47 (12) 48p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (11) Apr 77		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

A condensed version of this report can be found in the Proceedings 1977 Annual Reliability and Maintainability Symposium Paper 1469, pages 385-390

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cost Model, Failures, Hazard Rate, Reliability, Trade-off Analysis

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

Specific attention is currently being addressed to the overall cost of the reliability specification as early as the development stage in an equipment's life cycle. In order to assess the impact of changes in an equipment's reliability specification, it must be possible to predict and monitor the effects of such changes on an equipment's reliability testing and field support costs.

This research report elaborates the respective cost and reliability improvements resulting from six major reliability program efforts prior to an → over

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037620

20. ABSTRACT (Continued)

equipment's field deployment. The six efforts are:

(1) the design review;

(2) the reliability prediction program;

(3) the failure mode, effects, and criticality analysis (FMECA);

(4) the parts program, in which MIL-STD and high reliability parts are selectively used in place of commercially available parts;

(5) the reliability testing programs; and

(6) the Burnin test.

One hundred sixty exhaustive "policies" are analyzed with respect to their cost and resultant reliability. Each policy is a specific combination of the reliability program tasks imposed. The total policy cost is the sum of the reliability program cost and the expected field support cost after the equipment is deployed.

The Field Support costs are assumed inversely related to the reliability level, as measured by the Mean Time Between Failure (MTBF), achieved prior to deployment.

The model is computerized and sorts the total policy cost in ascending order. The optimal policy and the resultant MTBF corresponding to the minimum total cost are the outputs of the model.

COSTER is not a Life Cycle Cost Model, but is used as a comparative analysis tool for selecting the best reliability program plan and the optimal value of MTBF for the reliability specification.

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INTRODUCTION

Specific attention is currently being addressed to the overall cost, throughout an equipment's life, of the reliability specification as early as the Required Operational Capability (ROC) stage in an equipment's development. This requires that the principal effects of any reliability specification changes on the equipment's testing and support costs be predicted and subsequently monitored throughout the equipment's contract duration, in order to verify the predicted values.

MOTIVATION FOR COST OPTIMIZING SYSTEM TO EVALUATE RELIABILITY (COSTER)

Because the support cost of typical Electronics Equipments typically exceeds the initial acquisition cost by at least a factor of five, it behooves the Department of Defense, and the Army, in particular, to improve the reliability of their future equipment. The reliability improvement is achieved in an equipment's development phase with less expense than during the production phase and subsequent field deployment. It is important to realize, however, that there is a "trade-off" in terms of the money expended in order to achieve a particular level of reliability and the resultant cost savings experienced after the equipment has been fielded. The savings is a result of the decreased number of field failures experienced over a particular lifetime, because of the equipment's improved mean time between failures (MTBF).

In order to quantitatively analyze this cost tradeoff, a computerized cost model (COSTER) was developed. The model is capable of determining the total cost and subsequent reliability level achieved after implementing a reliability program, or series of programs, during the equipment's development stage.

Once an equipment has entered the production phase of its life cycle, it typically undergoes Production Sampling Tests and/or Burn-in prior to field deployment. COSTER enumerates the resultant MTBF and cost associated with both these production programs. It also calculates the expected support cost, over the equipment's expected life, once the equipment is fielded. The model is applicable at the time the Required Operational Capability (ROC) document is written. The ROC contains both the minimum acceptable value (MAV) and the best operational capability (BOC) of an equipment, as measured by its MTBF, in hours. The specified equipment MTBF, θ_0, will, in general, be somewhere between the MAV and the BOC.

The ultimate objective of the model was to determine this optimal value of the specified MTBF, θ_0^*, as well as the required reliability program necessary to achieve it. This optimal value of MTBF will yield the minimum total cost for the combined development, production, and field usage phases of the equipment's life. The model will not determine the equipment's total life cycle costs, but will be used as a comparative analysis tool for selecting the best reliability program plan and the optimal value of MTBF for the reliability specification.

The model postulates that some minimal reliability will be achieved with no reliability effort. This minimal reliability is "improved" as the various tasks of the reliability program are completed. The reliability "improvement" for each reliability task is calculated and the associated cost is accumulated throughout the system's development and production phases. The complete model, covering development, production testing, and field usage phases, is an exhaustive evaluation of the cost and reliability "improvement" for all combinations of program tasks.

MAJOR RELIABILITY PROGRAMS

During a development contract, a reliability program is generally conducted in accordance with MIL-STD-785. Nine major tasks comprise the reliability program, and have been identified as major cost and reliability "improvement" areas:

(a) Parts Program
(b) Reliability Design Review
(c) Reliability Prediction
(d) Failure Mode, Effects, and Criticality Analysis (FMECA)
(e) Reliability Growth Test
(f) Reliability Demonstration Test
(g) Reliability Qualification Test
(h) Production Sampling Test
(i) Burn-In

Even though there are nine basic reliability program tasks, there were only 160 (not 2^9 or 512) possible combinations of tasks because of inherent program restrictions which preclude some combinations from consideration. For example, the Reliability Prediction may only be performed if the Design Review is accomplished; also, the FMECA is permitted only when both the Design Review and Reliability Prediction are performed. Each of the 160 combinations is known as a policy.

Policy 1 yields the field support cost and total program cost when no reliability program is implemented. In this case the total policy cost equals the field support cost. Policy 160 yields the cost and resultant MTBF's for all possible reliability tasks; it also contains the cumulative reliability program costs, the field support costs, and the total policy cost of the reliability program and field support.

Table 1 elaborates the program tasks for each of the 160 policies, while Table 2 contains a list of all the computer subroutines, together with their prescribed functions.

POLICY	PARTS	REL DES REV	REL PREDICTION	FMECA	GROWTH TEST	DEMO TEST	QUAL TEST	PROD SAMP TEST	BURN IN
1									
2	X								
3		X							
4	X	X							
5		X	X						
6	X	X	X						
7		X	X	X					
8	X	X	X	X					
9						X			
10	X					X			
11		X				X			
12	X	X				X			
13		X	X			X			
14	X	X	X			X			
15		X	X	X		X			
16	X	X	X	X		X			
17						X	X		
18	X					X	X		
19		X				X	X		
20	X	X				X	X		
21		X	X			X	X		
22	X	X	X			X	X		
23		X	X	X		X	X		
24	X	X	X	X		X	X		
25						X		X	
26	X					X		X	
27		X				X		X	
28	X	X				X		X	
29		X	X			X		X	
30	X	X	X			X		X	
31		X	X	X		X		X	
32	X	X	X	X		X		X	
33						X	X	X	
34	X					X	X	X	
35		X				X	X	X	
36	X	X				X	X	X	
37		X	X			X	X	X	
38	X	X	X			X	X	X	
39		X	X	X		X	X	X	
40	X	X	X	X		X	X	X	
41									X
42	X								X
43		X							X
44	X	X							X
45		X	X						X
46	X	X	X						X
47		X	X	X					X
48	X	X	X	X					X
49						X			X
50	X					X			X
51		X				X			X
52	X	X				X			X
53		X	X			X			X
54	X	X	X			X			X
55		X	X	X		X			X
56	X	X	X	X		X			X
57						X	X		X
58	X					X	X		X
59		X				X	X		X
60	X	X				X	X		X
61		X	X			X	X		X
62	X	X	X			X	X		X
63		X	X	X		X	X		X
64	X	X	X	X		X	X		X
65						X		X	X
66	X					X		X	X
67		X				X		X	X
68	X	X				X		X	X
69		X	X			X		X	X
70	X	X	X			X		X	X
71		X	X	X		X		X	X
72	X	X	X	X		X		X	X
73						X	X	X	X
74	X					X	X	X	X
75		X				X	X	X	X
76	X	X				X	X	X	X
77		X	X			X	X	X	X
78	X	X	X			X	X	X	X
79		X	X	X		X	X	X	X
80	X	X	X	X		X	X	X	X

Table 1. List of program tasks for all 160 Policies

POLICY	PARTS	REL DES REV	REL PREDICTION	FMECA	GROWTH TEST	DEMO TEST	QUAL TEST	PROD SAMP TEST	BURN IN
81					X				
82	X				X				
83		X			X				
84	X	X			X				
85		X	X		X				
86	X	X	X		X				
87		X	X	X	X				
88	X	X	X	X	X				
89					X	X			
90	X				X	X			
91		X			X	X			
92	X	X			X	X			
93		X	X		X	X			
94	X	X	X		X	X			
95		X	X	X	X	X			
96	X	X	X	X	X	X			
97					X	X	X		
98	X				X	X	X		
99		X			X	X	X		
100	X	X			X	X	X		
101		X	X		X	X	X		
102	X	X	X		X	X	X		
103		X	X	X	X	X	X		
104	X	X	X	X	X	X	X		
105					X	X		X	
106	X				X	X		X	
107		X			X	X		X	
108	X	X			X	X		X	
109		X	X		X	X		X	
110	X	X	X		X	X		X	
111		X	X	X	X	X		X	
112	X	X	X	X	X	X		X	
113					X	X	X	X	
114	X				X	X	X	X	
115		X			X	X	X	X	
116	X	X			X	X	X	X	
117		X	X		X	X	X	X	
118	X	X	X		X	X	X	X	
119		X	X	X	X	X	X	X	
120	X	X	X	X	X	X	X	X	
121					X				X
122	X				X				X
123		X			X				X
124	X	X			X				X
125		X	X		X				X
126	X	X	X		X				X
127		X	X	X	X				X
128	X	X	X	X	X				X
129					X	X			X
130	X				X	X			X
131		X			X	X			X
132	X	X			X	X			X
133		X	X		X	X			X
134	X	X	X		X	X			X
135		X	X	X	X	X			X
136	X	X	X	X	X	X			X
137					X	X	X		X
138	X				X	X	X		X
139		X			X	X	X		X
140	X	X			X	X	X		X
141		X	X		X	X	X		X
142	X	X	X		X	X	X		X
143		X	X	X	X	X	X		X
144	X	X	X	X	X	X	X		X
145					X	X		X	X
146	X				X	X		X	X
147		X			X	X		X	X
148	X	X			X	X		X	X
149		X	X		X	X		X	X
150	X	X	X		X	X		X	X
151		X	X	X	X	X		X	X
152	X	X	X	X	X	X		X	X
153					X	X	X	X	X
154	X				X	X	X	X	X
155		X			X	X	X	X	X
156	X	X			X	X	X	X	X
157		X	X		X	X	X	X	X
158	X	X	X		X	X	X	X	X
159		X	X	X	X	X	X	X	X
160	X	X	X	X	X	X	X	X	X

Table 1. (Continued)

SUBROUTINE	FUNCTION PERFORMED
GROWUP	Reads input data from disk files. Reads the number of parts in each class e.g. Resistors, Capacitors, Analog IC's, etc., as well as the respective component failure rates and costs from the disk files, ARRAY1, ARRAY2. It also reads initial guess for θ_0, as well as other variable input data from the terminal.
GRDAT1	Prints out the variable input data elements for verification by the COSTER user.
START	Initializes cost to zero.
BASEFR	Calculates the basic failure rate and resultant MTBF when all component parts are assumed commercial, i.e. at screening level D.
PARTS	Calculates the total parts cost and resultant MTBF after the desired screening level is chosen for each parts class.
DESREV	Calculates the cost and achieved MTBF after a Design Review Program is imposed
DESRP	Calculates the cost and achieved MTBF after a Reliability Prediction Program is imposed
DESFM	Calculates the cost and achieved MTBF after the Failure Mode, Effects, and Criticality Analysis (FMECA) is imposed
RGRWTH	Calculates the expected cost and required reliability growth rate necessary to meet the specified MTBF by the end of Engineering Development
DMOTST	Using appropriate test plan specifications, DMOTST calculates the expected cost, and the "improved" MTBF subsequent to the Reliability Demonstration Test. It allows a maximum of two reruns due to test failure
QTST	Using appropriate test plan specifications, QTST calculates the expected cost, and the "improved" MTBF subsequent to the Qualification Test
PRDTST	Using appropriate test plan specifications, PRDTST calculates the expected cost, and the "improved" MTBF subsequent to the Production Sampling Test
BURNIN	Calculates the expected cost of the Burn-In Test

Table 2. List of Computer Program Subroutines and their Respective Functions

SUBROUTINE	FUNCTION PERFORMED
FLDSPT	Calculates the expected cost of field support throughout system's expected deployment life
SORDAT	Sorts total costs, in increasing order for all 160 policies and writes on a disk file
OUTDAT	Prints output of the sorted costs

Table 2. (Continued)

The cost model is a comparative analysis tool used to monitor the effects of changes in the reliability program on an equipment's expected total cost throughout its lifetime. The expected total cost is the sum of the reliability program costs, and the field support costs.

Since the reliability program costs are expected to be monotonically increasing with increasing reliability, and the field support costs are expected to be monotonically decreasing with increasing reliability, then a plot of total cost versus reliability (MTBF) will be U-shaped, indicating that there is an optimal value of MTBF which will yield the lowest total cost. The resultant curve is shown in Figure 1.

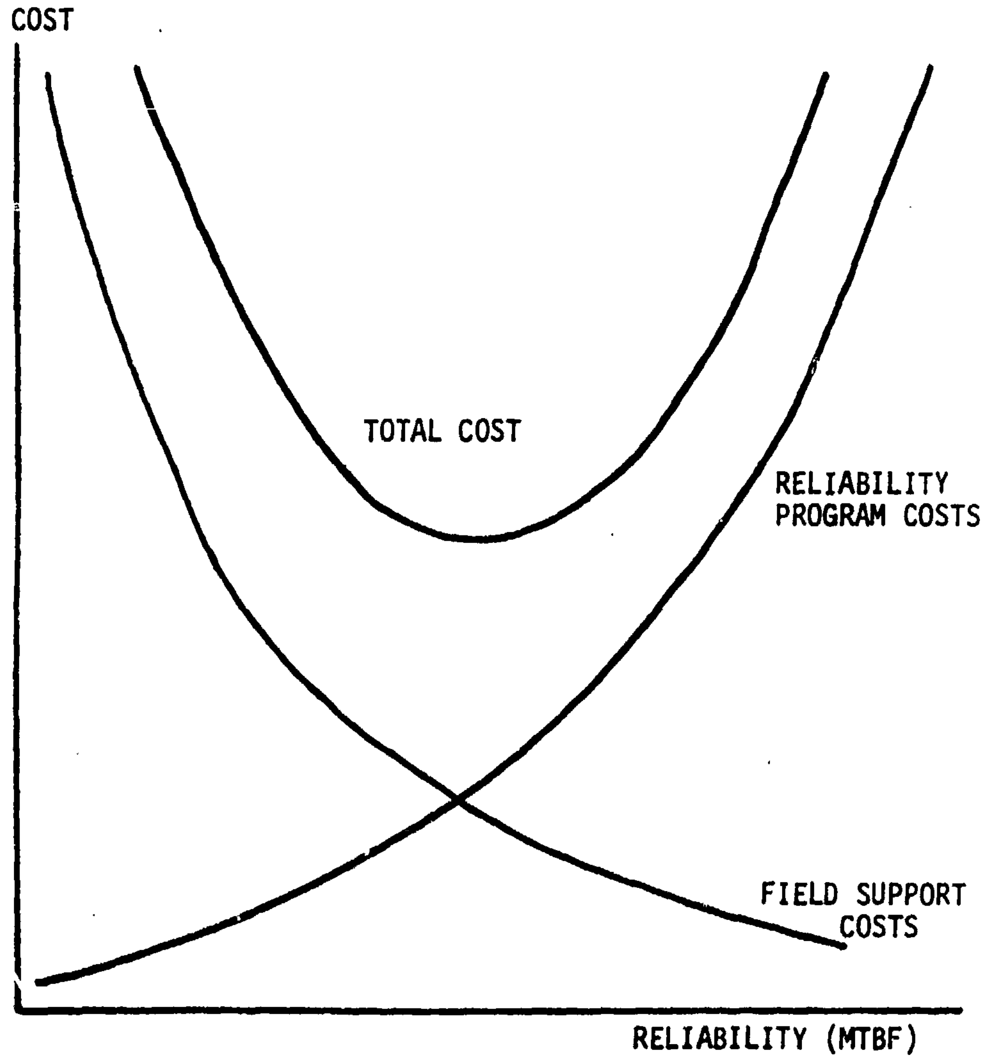


Figure 1. Plots of Cost versus Reliability

REQUIRED INPUT DATA

The subroutine GROWUP is used to read the input data files containing the following information (the number of test samples, test time multiples, and maximum allowable number of failures are determined in accordance with the appropriate test plan as prescribed in MIL-STD-781B):

a) Specified MTBF - θ_0

b) Percentage of the respective parts classes at each of the five screening levels

c) The test time, expressed in multiples of θ_0, for the Demonstration Test, Qualification Test, and Production Sampling Test - DT781, QT781, and PT781, respectively

d) The maximum allowable number of failures for the Demonstration Test, Qualification Test, and Production Sampling Test - DKF, QKF, and PKF, respectively

e) The number of test samples for the Demonstration Test, Qualification Test, and Production Sampling Test - DN, QN, and PN, respectively

f) The testing cost ($ per chamber hour) for the Demonstration Test, Qualification Test, and Production Sampling Test - DCJ, QCJ, and PCJ, respectively

g) The cumulative Reliability Growth testing hours through advanced development - T_1

h) The cumulative Reliability Growth testing hours through engineering development - T_2

i) The minimum acceptable value of MTBF, and MAV - XMAV

j) The minimum total test time for the Burnin test - T

k) The required number of failure-free hours to pass the burnin test - H

l) Testing cost ($ per chamber hour) for the Burnin test - BCJ

m) The number of equipments per chamber for the Burnin test, and the Reliability Growth test - BN and GN, respectively

n) The total number of equipments to be fielded - QUANT

o) The expected equipment usage life - LIFE

p) Equipment Usage

HRS - (Hours/Day)
DAYS - (Days/Week)

q) Repair cost per fielded equipment - CREP

r) Operating environment - ENVIR

1. Ground Benign $\Pi = 0.2$
2. Ground Fixed $\Pi = 1.0$
3. Airborne Inhabited $\Pi = 3.0$
4. Airborne Uninhabited $\Pi = 6.0$

The factor Π is used to modify the predicted failure rate with respect to the operating, or usage, environment.

PARTS/SCREENING EFFECTS MODEL

The goal of the specific parts program analysis is to be able to identify and quantify the cost and reliability (in terms of MTBF) effects of specific screening levels for each of the equipment components, Analog IC's, Digital IC's, Field Effect Transistors, etc. This is used in conjunction with the other subroutines to develop the overall development, production, and field usage cost model.

Kellington (3) determined the effects of building more reliability into electronics systems by using solid state components of various quality levels. Results for a particular equipment in development, using the SETON logistics support model, indicated that the lowest possible initial acquisition cost is not likely to yield the lowest life cycle support cost.

Electronic parts are frequently selected from several levels of quality which provide the designer with the ability to meet performance and reliability requirements in the most economic manner.

Quality Level A is the best quality that can be procured and is generally obtained only by special manufacturing process controls and screening beyond that offered by "off-the-shelf" high reliability military specification programs.

Quality Level B is the best available "off-the-shelf". It will generally be obtained under military or equivalent high reliability programs requiring rigid manufacturing process controls and extensive screening, including burn-in or wear-in and parameter drift screens where applicable. Level B is the "top-of-the-line" part for general high reliability usage.

Quality Level C is a less expensive version of quality level B and will also generally be obtained under military or equivalent high reliability programs. Level C requires the same rigid manufacturing process controls and screening as level B, except burn-in or wear-in and certain parameter drift screens may be omitted to cut down on part costs.

Quality Level D is defined in accordance with MIL-M-38510 class C, and is generally the best quality level available without the cost of high reliability process controls and screening. Level D can be selected from the same manufacturers as Levels B and C with consideration to their in-house quality assurance and screening provisions.

Quality Level E, while not a true screening level, is defined as the approximate quality level of commercial "off-the-shelf" items. These items are generally cheaper and usually have higher failure rates than any of the four previous screening levels.

Table 3 describes the correspondence between the screening levels for subroutine PARTS, and the levels defined in MIL-STD-217B.

Program Screening Level	MIL-STD-217B Screening Level	Description
A	A	MIL-M-38510
B	B	MIL-M-38510
C	B1, B2	MIL-STD-883 Method 5004, Class B
D	C	MIL-M-38510 Class C
E	D	Commercial or Non-MIL-STD (No Screening Beyond Manufacturer's Regular QA Practice)

Table 3. Description of each of the Five Basic Screening Levels Considered in PARTS Subroutine.

The subroutine PARTS considers the following 11 basic parts classes:

a) Analog IC's
b) Digital IC's
c) Field Effect Transistors
d) NPN Transistors
e) PNP Transistors
f) General Purpose Diodes
g) Zener Diodes
h) Microwave Detecting Diodes
i) Resistors
j) Capacitors
k) Inductors

The subroutine PARTS reads the number of components, the failure rate of each component class (per 10^6 hours), and the respective component cost from two disk files, ARRAY1 and ARRAY2. Assuming a series reliability configuration among all components, it calculates the overall screening cost, resultant failure rate and MTBF (=10^6/Failure Rate) for the desired configuration. The screening cost is just the overall cost of the parts at the particular screening levels chosen. One version of the subroutine is "conversational" and requests from the user the respective screening level for each of the component types. Table 4 contains the array of failure rate and cost for each of the respective screening levels.

The parts program calculates the achieved improvement in MTBF at the higher component screening levels with assumed redundancy over the entire unit. The improvement due solely to unit redundancy, as opposed to individual class redundancy, was 1.5, for exponential failures, i.e. $\theta^{(R)}/\theta^{(NR)} = 1.5$, where $\theta^{(R)}$ is the achieved MTBF with unit redundancy, and $\theta^{(NR)}$, that without redundancy.

The proof is as follows:

Consider a unit with N components in logical series. Define $R^{(R)}(t)$ as the reliability function of the redundant unit, and $R^{(NR)}(t)$ the reliability function of a non-redundant unit. Define $r_i(t)$ as the reliability function of the ith component. For single unit redundancy,

$$R^{(R)}(t) = 1 - (1 - \prod_{i=1}^{N} r_i(t))^2$$

$$= 1 - \{1 - 2 \prod_{i=1}^{N} r_i(t) + \left[\prod_{i=1}^{N} r_i(t)\right]^2\}$$

$$= 2 \prod_{i=1}^{N} r_i(t) - \left[\prod_{i=1}^{N} r_i(t)\right]^2$$

For a non-redundant unit,

$$R^{(NR)}(t) = \prod_{i=1}^{N} r_i(t)$$

It is desired to obtain the ratio

$$\theta^{(R)}/\theta^{(NR)} = \frac{\int_0^\infty R^{(R)}(t)}{\int_0^\infty R^{(NR)}(t)}$$

For an exponential distribution of time to failure, $r_i(t) = \exp(-\lambda_i t)$, where λ_i is the constant hazard rate of the ith component type.

$$R^{(R)}(t) = 2 \exp(-\sum_{i=1}^{N} \lambda_i t) - \exp(-2 \sum_{i=1}^{N} \lambda_i t)$$

$$R^{(NR)}(t) = \exp(-\sum_{i=1}^{N} \lambda_i t)$$

Substituting the reliability function into the integral expression for the MTBF yields:

$$\theta^{(R)}(t) = \int_0^\infty 2 \exp(-\sum_{i=1}^{N} \lambda_i t)dt - \int_0^\infty \exp(-2 \sum_{i=1}^{N} \lambda_i t)dt$$

$$= 2/ \sum_{i=1}^{N} \lambda_i - 1/ 2 \sum_{i=1}^{N} \lambda_i = 1.5/ \sum_{i=1}^{N} \lambda_i$$

$$\theta^{(NR)}(t) = \int_0^\infty \exp(-\sum_{i=1}^{N} \lambda_i t)\, dt = 1/ \sum_{i=1}^{N} \lambda_i$$

Taking the ratio of the achieved MTBF with redundancy to the MTBF without redundancy yields:

$$\theta^{(R)}(t)/\theta^{(NR)}(t) = 1.5$$

SCREENING LEVEL

CLASS	A		B		B1-B2		C		D	
	FR	COST	FR	COST	FR	COST	FR	COST	FR	COST
ANALOG IC's	0.0432	33.1	0.0864	13.1	0.648	10.6	1.296	6.7	1.50	3.00
DIGITAL IC's	0.00186	37.5	0.00365	17.5	0.0292	16.5	0.27	4.0	0.40	1.50
FET's	0.063	3.5	0.1638	1.75	0.315	1.35	0.63	1.05	0.80	0.75
NPN's	0.01335	0.9	0.03471	0.45	0.06675	0.25	0.1335	0.2	0.20	0.15
PNP's	0.0195	0.9	0.0501	0.45	0.0975	0.25	0.195	0.20	0.25	0.15
DIODES	0.00525	1.9	0.0137	0.93	0.02625	0.165	0.0525	0.127	0.075	0.08
ZENER DIODES	0.0125	2.0	0.0325	1.5	0.0625	0.43	0.125	0.35	0.175	0.15
MW DIODES	0.36	7.75	0.72	6.55	0.72	6.55	1.80	6.0	2.0	3.25
RESISTORS	2.00	0.03	2.00	0.03	2.00	0.03	2.00	0.03	2.0	0.03
CAPACITORS	5.00	0.10	5.00	0.10	5.00	0.10	5.00	0.10	5.0	0.10
INDUCTORS	0.85	0.30	0.85	0.30	0.85	0.30	0.85	0.30	0.85	0.30

TABLE 4. Array of Failure Rates for each Respective Screening Level (Data contained in sequence file ARRAY2).

BASE FAILURE RATE CALCULATION

Subroutine BASEFR calculates the basic cost and resultant MTBF when all of the parts are assumed at screening level E (commercial parts) and no reliability program is imposed.

Its output yields the resultant MTBF and parts cost when no parts screening is imposed and no other reliability programs are imposed. It generally will result in the highest Field Support costs since the inherent MTBF will be the lowest. It is used primarily to give the expected results when no reliability program is imposed.

RELIABILITY DESIGN PROGRAM

DESIGN REVIEW MODEL

The design review task encompasses those tasks outlined in paragraph 5.2.7 of MIL-STD-785A. Mercurio (4) developed cost and reliability improvement relationships based upon a linear regression analysis on 10 specific equipments.

Mercurio found that the reliability improvement, in terms of MTBF, increased by a factor of 1.11 after a design review program. The reliability improvement and cost relationships are calculated in subroutine DESREV, and are given below for reference.

THETA = 1.11*XBRI,

where THETA is the MTBF realized after a design review program, and XBRI is the initial MTBF expected without any reliability design program.

The cost of the design review is calculated as a fixed percentage of the reliability prediction programs using Mercurio's basic relationships given below. CDR is the cost of the design review program, CRP is the cost of the reliability prediction, and CFM is the cost of the failure mode, effects and criticality analysis. In Mercurio's notation, all costs are in units of "man-days".

Design Review	CDR = 0.023*NP
Reliability Prediction	CRP = 0.101*NP
FMECA	CFM = 0.090*NP

where NP is the total number of parts within any equipment configuration.

Since CDR/CRP = 0.023/0.101, then

CDR = (0.023/0.101)*CRP.

RELIABILITY PREDICTION MODEL

Mercurio found that the MTBF increased by a factor of 1.428 when a reliability prediction was performed. The incremental reliability improvement and cost of the reliability prediction model are computed in the subroutine DESRP. Since reliability prediction can only be done if a design review was performed, then the reliability improvement equation contains the factor 1.11 resulting from the design review program.

THETA = 1.428*1.11*XBRI, where

THETA is the MTBF realized after the reliability prediction program and XBRI is the initial MTBF expected without any reliability design program.

The cost of the reliability prediction was based on an estimated per part prediction cost for each of the respective part categories. Table A2, in the Appendix, contains the reliability prediction costs per component type as a function of the number of each type of part. It is specifically oriented to the high speed serial Data Buffer.

Defining NPC as the number of basic parts classes, CC(I) as the reliability prediction cost per component type I, and NUMBER(I) as the number of parts within each parts class, then the total reliability prediction cost is

$$CRP = \sum_{I=1}^{NPC} NUMBER(I) * CC(I).$$

FMECA MODEL

Mercurio found that the MTBF subsequent to a failure mode, effects, and criticality analysis (FMECA) increased by a factor of 1.296 over that achieved with the reliability prediction program. The reliability improvement and cost of a failure mode, effects, and criticality analysis is computed in subroutine DESFM. Again, since the FMECA is only performed if both the design review and the reliability prediction are performed, then the improvement factors 1.428, and 1.11 are included.

THETA = 1.296*1.428*1.11*XBRI, where

THETA is the MTBF realized after the FMECA, and XBRI is the initial MTBF expected without any reliability design program.

Since CFM/CRP = 0.101/0.090, then

CFM = (0.101/0.090)*CRP

Figure 2 contains a flow chart of the potential reliability improvements subsequent to each of the three reliability program elements. The variable XBRI is the equipment's MTBF just prior to the design review program and C is the cumulative cost incurred before the design review program is initiated.

RELIABILITY TESTING MODELS

There are five basic testing models considered in the COSTER program:

(a) Reliability Growth Testing
(b) Reliability Demonstration Testing
(c) Qualification Tests
(d) Production Sampling Tests
(e) Burn-In Tests

COSTER is structured in such a way that an improvement in MTBF will result after the Reliability Growth Test, the Demonstration Test, the Qualification Test, and the Production Sampling Test.

SYSTEM RELIABILITY GROWTH METHODOLOGY

Failures of an equipment during a prescribed mission can be classified into two types, either they are inherent failures, or assignable cause failures. Each type may occur during a mission; hence, the failure occurrences are chance events.

Inherent failures are those whose assignable causes cannot be determined, and are due to the interaction of the system and the environment at the time of the impending failure. Inherent failures cannot be eliminated by a design change. Assignable cause failures are those which can be eliminated by a design change or by some other means. This may involve part substitution with more stringently screened parts, tighter quality control procedures, tolerance changes or other design changes. The important distinction between this type of failure and an inherent failure is that a definite assignable cause has been established and its future occurrence can be effectively prevented. It should be noted, however, that the occurrence of such assignable cause failures during a given mission is nevertheless due to chance, i.e. a combination of environment and other circumstances brings about the failure.

During reliability growth testing, "test-locate-fix" sequences will systematically eliminate assignable cause failures. It is assumed, however, that no new failures are introduced in making the necessary design or procedural changes. Figure 3 contains a schematic illustration of the growth of an equipment's reliability function.

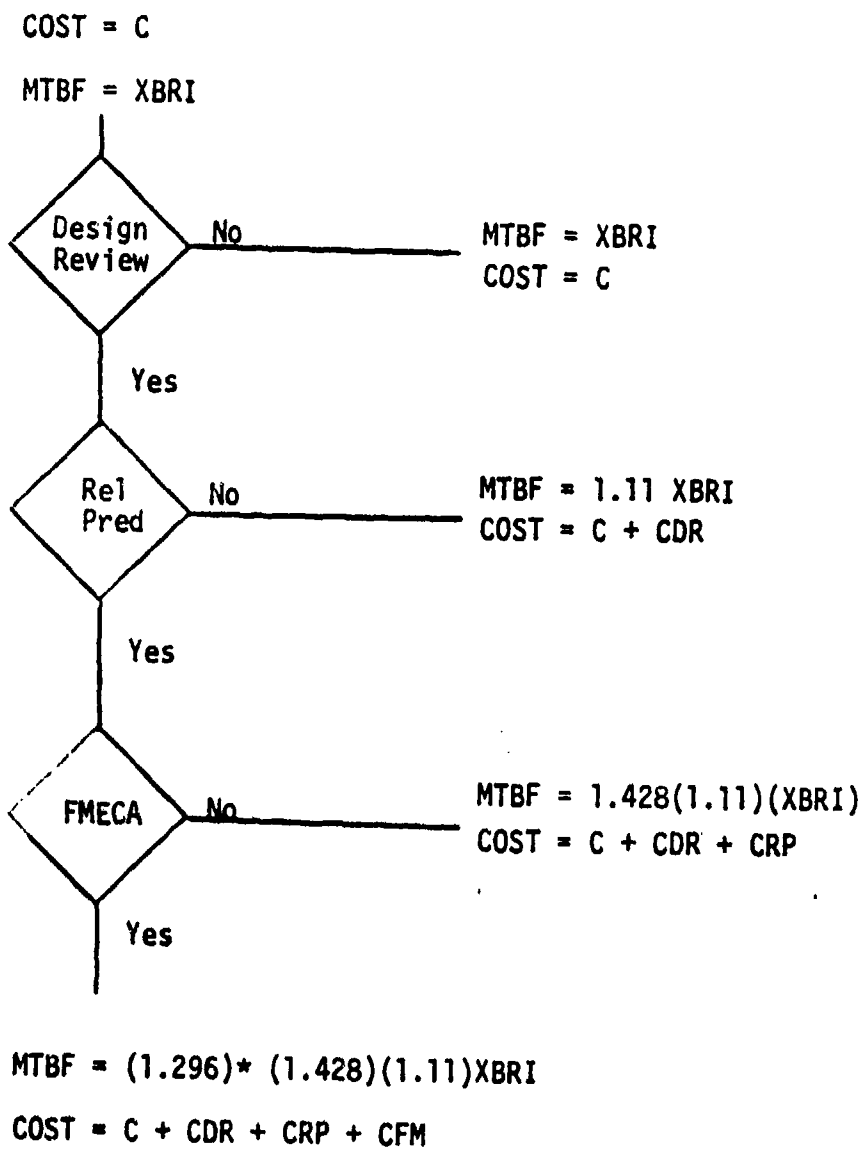


Figure 2. Flow Chart Containing Possible Reliability Design Program Options.

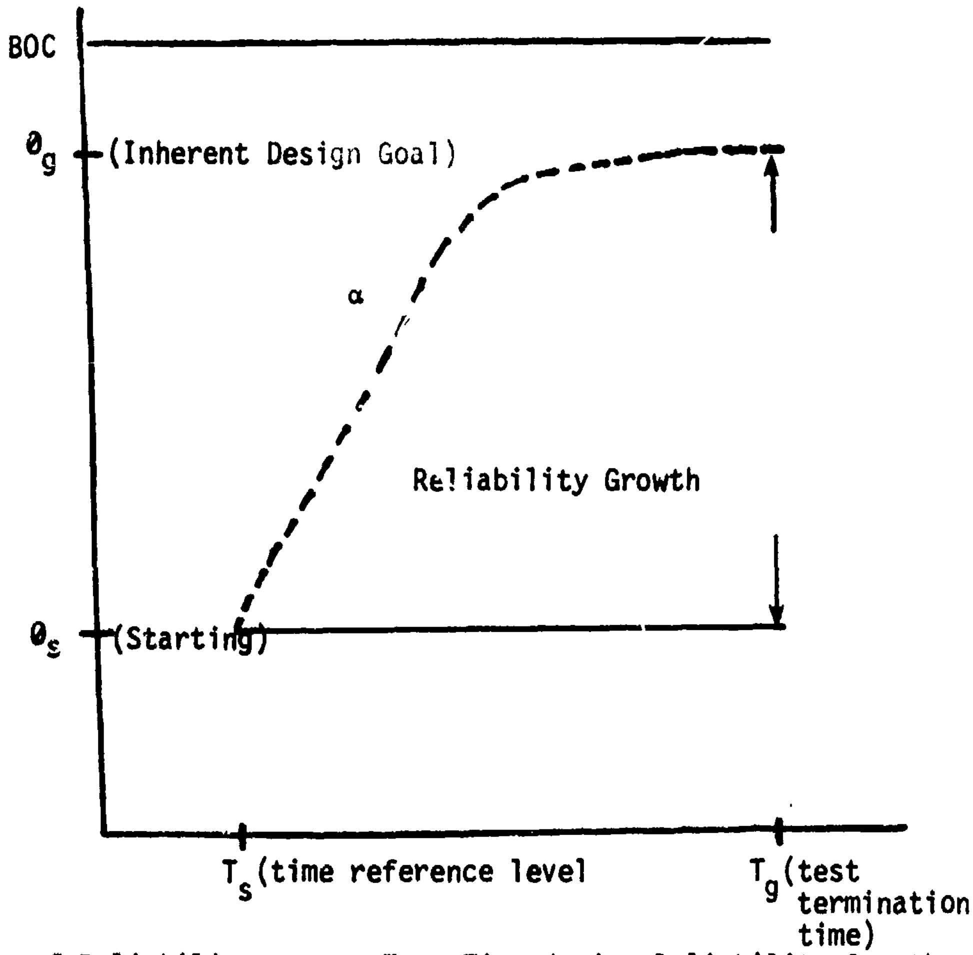


Figure 3. Plot of Reliability versus Test Time during Reliability Growth Testing

Duane (1) found that a plot of system MTBF versus cumulative test time yielded a straight line when plotted on log-log paper. Thus an appropriate analytical form for the reliability, expressed as the system MTBF, versus the reliability growth test time is

$\theta_c(T) = T^{\alpha}/K$, where

$\theta_c(T)$ is the cumulative MTBF after T hours of reliability growth testing,

α is the reliability growth rate, and

K is a proportionality constant usually determined by the MTBF after 100 hours of testing,

$K = 100^{\alpha}/\theta(100)$.

With a design goal of θ_g, after T_g hours of growth testing, and a starting MTBF of θ_s after T_s hours, the reliability growth rate is calculated as follows:

$$\alpha = \frac{\log \theta_g - \log \theta_s}{\log T_g - \log T_s}$$

Using common logarithms, and an initial test time of 100 hours, the formula for the growth rate becomes:

$$\alpha = \frac{\log \theta_g - \log \theta_s}{\log T_g - 2}$$

The instantaneous MTBF is calculated by dividing the cumulative values by $(1-\alpha)$:

$$\theta_I(T) = \theta_C(T)/(1-\alpha)$$

The cost of performing a reliability growth test is directly proportional to the amount of time required to perform the test; it is also a function of the reliability growth rate, α.

If a growth chamber contains as many as GN equipments, then the expected reliability growth cost is given by

CGROW = CGT * (T2 - 100.)/GN, where

T2 is the cumulative test time through the end of engineering development, and CGT is the hourly cost of performing the test.

DEMONSTRATION, QUALIFICATION, AND PRODUCTION SAMPLING TESTS

The cost relationships for reliability testing are directly dependent upon the test plan selected, the specified MTBF, the achieved MTBF just prior to the initiation of the reliability test, the expected time to complete the test, and the cost per chamber hour for performing the test. The reliability improvement relationships are based on the probability of test failure and the probability of corrective action being implemented to remove failure modes.

Reliability Demonstration is the evaluation, through operation, of the capability of an equipment to meet a specified reliability value. If no design changes are made, inherent reliability remains constant while demonstrated reliability, at a given level of confidence, increases as more operating time or test cycles are accrued. Consequently, when the inherent reliability is reasonably high, the demonstrated reliability will approach actual reliability asymptotically as more and more time/cycles are accumulated.

The Qualification Test is performed on the first production lot. This test is usually as severe as the reliability demonstration test conducted during the development phase and is intended to assure that production processes have not degraded the reliability of the equipment.

The Production Sampling Tests are shorter duration reliability tests run periodically during the production phase. These tests are intended to assure that the reliability level has not been degraded during the production phase.

For fixed length test plans, MIL-STD-781B specifies the maximum number of failures permitted in order to pass the test. The variables DKF, QKF, and PKF are defined as the maximum number of permissible failures for the Demonstration, Qualification, and Production Sampling Tests, respectively. The probability of passing any of the tests is given by a cumulative Poisson sum:

$$P_r = \sum_{I=0}^{DKF,\ QKF,\ PKF} \frac{u^I * e^{-u}}{I!}, \text{ where}$$

$$u = \frac{DT781*\theta_0}{\theta}, \quad \frac{QT781*\theta_0}{\theta}, \text{ or } \frac{PT781*\theta_0}{\theta}$$

for each of the three respective tests;

θ_0 is the specified equipment MTBF, and
θ is the instantaneous MTBF during the test.

DT781, QT781, and PT781 are the respective fixed length test time durations, in multiples of θ_0.

The equation for the improvement in MTBF as a result of reliability testing is expressed as:

$$\theta_T = (1-P_R)^2\, \theta + \theta,$$

where P_R is the probability of passing the specified test given that the true MTBF = θ.

θ = MTBF achieved prior to reliability testing
θ_T = MTBF achieved after reliability testing

As the probability of passing the test increases, the probability of recycling through the design and parts program decreases, resulting in a smaller expected increase in MTBF. Conversely, as the probability of rejection

$(1-P_R)$ increases, the probability of recycling through the design and parts program increases, resulting in a larger expected increase in MTBF. This is expressed in the MTBF improvement equation as the quantity $(1-P_R)^2 * \theta$.

For the demonstration test, the cost of testing is a function of the required test duration, $(DT781)*\theta_O$, as well as the probability of failing the test $(1-P_r)$, and having to implement corrective action. The corrective action is the possible reimplementation of the parts program and design review in order to increase the equipment's MTBF during the specified testing routine.

The testing cost for each iteration of the Demonstration Test is:

$$CDT = (DT781*\theta_O/DN) * DCJ + (1-P_r) * \{(CP+CD) + ((DT781*\theta_O/DN)*DCJ)\}$$

where the first term is the cost of running the fixed length test and the second term is the expected cost incurred due to the risk associated with failure of the demonstration test and subsequent corrective action. DN is the number of test samples for the demonstration test. CP and CD are the respective costs of the Parts program and Design stages.

If the acceptance probability, or probability of passing the Demonstration Test, has not reached the critical value of 0.8, the model compensates by reiterating the cost calculation to take into account the possibility of rerunning the test. The cost is dependent upon the fixed length duration, $(DT781*\theta_O)$, the sample size, DN, and the cost per chamber hour, DCJ. It is assumed that the chamber is large enough to contain the entire sample of DN equipments.

The Reliability Demonstration Test may be rerun as many as two times if the required acceptance probability has not reached 0.8. The acceptance probability, as calculated by the Poisson sum, will necessarily increase after each test rerun. This increase results from the expected reliability improvement subsequent to the Parts program, and Design stages. The test cost and reliability improvement portions of the model are exercised until either the probability of passing the test reaches 0.8 or until two retests have been performed, whichever occurs first. The reliability level calculated in DMOTST is assumed to be the reliability that has been achieved as a result of the reliability program instituted during the development phase of the life cycle.

The costs for the qualification and production sampling tests are calculated in the subroutines QTST and PRDTST, respectively. The basic model for the costs and reliability improvements as a result of the production testing is similar to that utilized for the development test. The major difference is that the production sampling model does not require that the additional cost for retest and corrective action implementation be accumulated. It was assumed that once an equipment has started production, it generally has met specification requirements. The probability of test failure is used implicitly to calculate the cost increase realized due to the risk of test failure. The reliability improvement realized as a result of production testing is minimal and actually can be regarded as a result of the contractor's motivation to maintain and possibly even improve quality prior to each production run. Another result of production testing, although less significant, is the decrease in the number of field usage failures because of the "burn-in effects" of the production sampling tests. Admittedly, the field usage effects are small, especially for small sample sizes relative to the lot size. The reliability level realized as a result of production testing is assumed to be the reliability level experienced in field usage.

BURN-IN MODEL

The burn-in test, when specified in an equipment's contract, is usually required for a minimum of T hours, the last H of which are required to be failure free. Thus the cost of the burn-in test depends upon the total expected time to complete the test and the cost, per chamber hour, of running the test. Since an equipment may not complete the required failure free period of H hours until the significant workmanship errors, causing the infant mortality failure, are corrected, the equipment's total expected test time will, in general, be larger than T hours.

It should be emphasized, however, that the equipment's MTBF, θ, is determined prior to the burn-in test. The duration of the required failure free period, H, has no effect on the equipment's MTBF; it is only used to eliminate the infant mortality failures.

The subroutine BURNIN calculates the expected time to completion and the expected cost of the burn-in test. Nelson (5) proposed a model for calculating the expected burn-in time which assumes that the region of infant mortality can be subdivided into m equal intervals each exhibiting a constant failure rate (See Figure 4). During each subinterval, the probability of H hours of failure free operation is exp (- L(I) H) where L(I) is the constant failure rate for the Ith subinterval. It is assumed that after T hours, the infant mortality failures will have ceased. During the first interval the hazard rate is L(m), and the probability of H hours of failure free operation is given by:

$$p(1) = \exp(-L(m) * H), \text{ likewise:}$$
$$p(2) = \exp(-L(m-1) * H),$$
$$p(3) = \exp(-L(m-2) * H),$$
$$\vdots$$
$$p(m) = \exp(-L(1) * H).$$

The preceding terminology is based on a linear decreasing failure rate curve, with slope of 45^{o}, to the horizontal region of constant failure rate, with L(1) = 1/Theta, where Theta is the equipment's MTBF going into the burn-in test.

It was required to make the restrictive assumption of a linearly decreasing failure rate curve in order to obtain mathematical estimates of the "piecewise" constant failure rates, L(1) ...L(m). Figure 3 contains a plot of hazard rate versus time.

The piecewise constant hazard rate, over the region $0 \leq t \leq T$ is defined by L(I) = 1/(Theta - (I-1)H), thus

L(1) = 1/Theta
L(2) = 1/(Theta-H)
L(3) = 1/(Theta-2H)
L(m) = 1/(Theta-(m-1)H), where

m = T/H is the number of intervals of piecewise constant hazard rate.

Consequently, the expected time required to complete the burn-in test, assuming a minimum of T hours of testing, with the last H hours being failure free is calculated as follows:

ETT = (T-H) + H * { P_r {H hours of failure free operation during the first interval}

+ P_r {H hours of failure free operation during the second interval given that there was a failure during the first interval of H hours}

+ P_r {H hours of failure free operation during the third interval given that both the first and second intervals had failures}

+...+

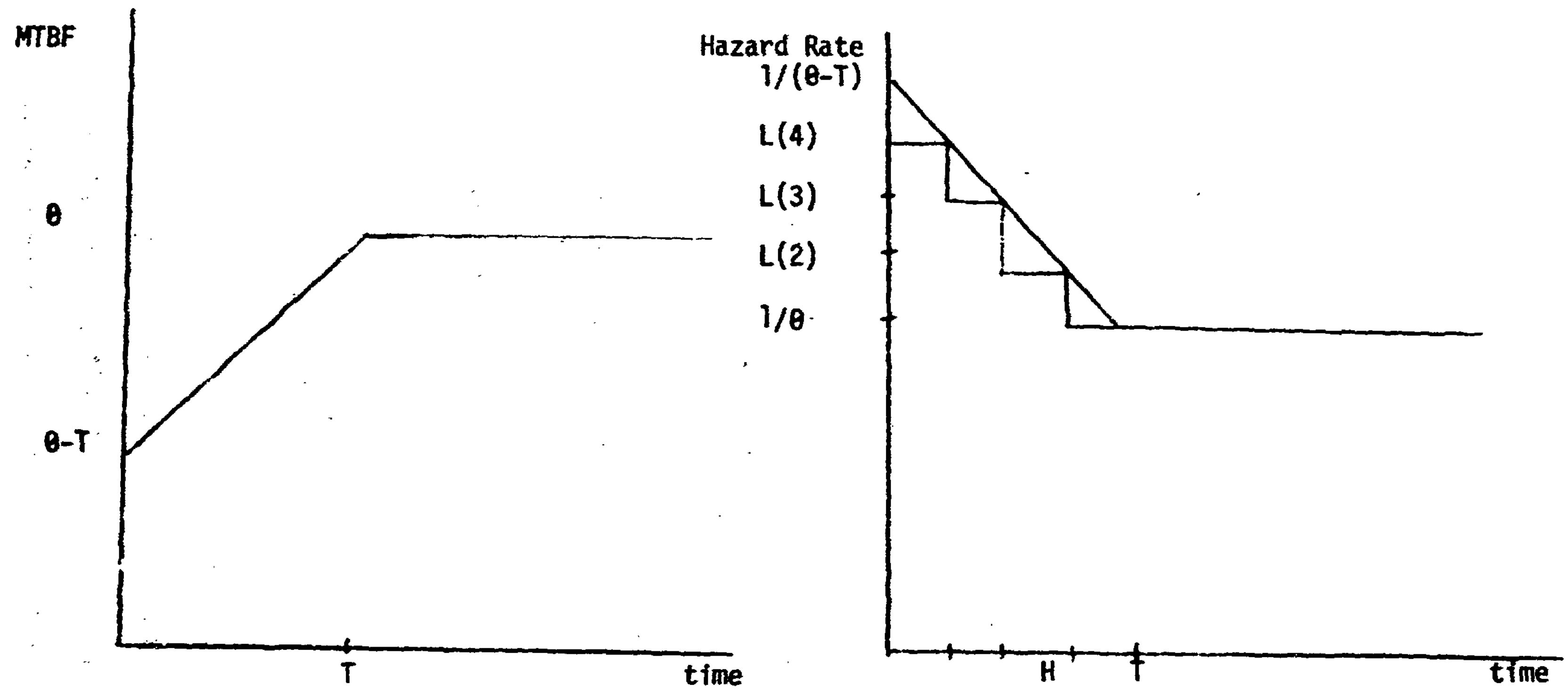
+ P_r {H hours of failure free operation during the last(mth) interval given that all of the prior intervals experienced failures} }

Therefore, the expected test time is:

ETT = (T-H) + H * {p(1) + 2p(2) *(1-p(1)) + 3p(3)*(1-p(2))*(1-p(1))

+...+ mp(m)*(1-p(m-1)) * (1-p(m-2)) *...* (1-p(1)}, where p(i)

is the probability of H hours of failure free operation during interval i.



DISCRETE

$L(i) = 1/\ \theta-(i-1)H\ ;\ 1 \leq i \leq m$
$L(i) = 1/\theta;\ i > m,\ \text{or if}\ \theta < H$

CONTINUOUS

$MTBF(t) = (\theta-T) + t;\ 0 \leq t \leq T$
$\quad = \theta;\ t > T$

CONTINUOUS

$L(t) = 1/(\theta-T) - t/\ \theta(\theta-T) + \{ (t-T)/ (\theta(\theta-T))\}\ U(t-T)$

Figure 4. Approximations to MTBF and Hazard Rate for an Equipment subject to a Burn-in Period, T, with the last H hours failure free.

However, for a total of QUANT equipments being produced, with chambers capable of holding BN equipments, the total expected chamber time is:

TETT = (QUANT/BN)*ETT.

As the chamber size, BN, increases, the total expected test time decreases, as exemplified by BN in the denominator.

Consequently, for the entire production lot of QUANT items, the total expected cost of burn-in is:

ECOST = BCJ * (QUANT/BN) * ETT, where BCJ is the cost per hour of using the chamber.

This cost is calculated assuming only one test chamber is used for the entire lot's burn-in test. If there were more than one chamber, then the total expected test time would be decreased by the factor 1/NC, where NC is the number of chambers.

FIELD SUPPORT MODEL

The costs incurred in the use phase of the equipments life cycle are calculated in the subroutine FLDSPT. Due to the early stage in the life cycle planned for utilization of the cost model, the field usage model is necessarily very general. An average cost of equipment repair is used in the model. The expected number of equipment failures is then calculated and multiplied by the cost of equipment repair to arrive at the field usage or operational phase costs. The basic equation to calculate the operational phase cost is

CFIELD = (CREP*QUANT*HRS*DAYS*LIFE*52)/θ + CREP*FLBI*QUANT

where:
- HRS = number of hours of equipment operation expected per day
- DAYS = number of days of equipment operation per week
- LIFE = useful life of the equipment, in years
- QUANT = number of equipments expected to be fielded
- θ = MTBF expected to be achieved in the field
- CREP = average cost of equipment repair
- FLBI = number of failures per equipment expected to occur if no burn-in program has been required

The expected number of failures per equipment if no burn-in program was imposed, FLBI, is calculated as follows:

$$FLBI = T/(\theta - T)\ ,\ \theta > T$$

$$= T/\theta\ ,\ \theta \leq T$$

where: T = Minimum Burn-In test time duration if BURNIN would have been run.

CONCLUSIONS

This analysis is not meant to be a complete life cycle cost analysis but only a model to compare the effects of various Reliability Program efforts on the sum of Field Support Costs and Reliability Program Costs. It is to be used as a technique for determining which of the allowable Reliability Programs should be implemented. Besides showing the effects on total costs, the model yields the resultant MTBF expected after each reliability program is implemented.

REFERENCES

1. Foster, J. W., and Craddock, W. T., "Estimating Life Parameters from Burn-In Data", Proceedings 1974 Annual Reliability and Maintainability Symposium, pp 206-209.

2. Hammer, H. W., "Reliability Demonstration Testing Using Failure-Free Trials", Proceedings 1974 Annual Reliability and Maintainability Symposium, pp 201-205.

3. Kellington, C. M., "The Impact of Solid State Parts Screening on Initial System Cost, Reliability and Life Cycle Maintenance Cost", USAECOM Technical Report, Ft. Monmouth, N.J. 07703, January 1975.

4. Mercurio, S. P., and Skaggs, C. W., "Reliability Acquisition Cost Study", RADC-TR-73-334 Final Technical Report, November 1973, AD 916286.

5. Nelson, A. Carl, "Life Cycle Cost Models", Prepared under Basic Agreement DAHC04-72-A-001, December 1974.

6. Perry, J. N., "Reliability Screening Techniques", Proceedings 1967 Annual Symposium on Reliability, pp 783-787.

7. Solomond, J.P., Marseglia, G.A., "Cost Optimizing System to Evaluate Reliability", Proceedings, 1977 Annual Symposium on Reliability and Maintainability, pp 385-390, Philadelphia, PA.

8. Weiss, G. H., and Dishon, M., "Some Economic Problems Related to Burn-In Programs", IEEE Transactions on Reliability, Vol R-20, No. 3, pp 190-195, August 1971.

9. Weiss, G. H., and Dishon, M., "Burn-In Programs for Repairable Systems", IEEE Transactions on Reliability, Vol R-22, No. 5, pp 265-267, December 1973.

APPENDIX A

APPLICATION OF COSTER TO A HIGH SPEED SERIAL DATA BUFFER

INTRODUCTION

The example equipment is a High Speed Serial Data Buffer currently in development. No Reliability Growth Program is required.

EQUIPMENT CONFIGURATION

The equipment is partitioned as sixteen (16) replaceable plug-in modules plus cabinet electronics. The configuration is illustrated in Figure A1. There are twelve (12) identical function channel data processing modules and one (1) each Receiver Common, Transmitter Common, Built-in-Test Equipment (BITE) and AC/DC Power Supply Modules. The functional equipment configuration is considered as a serial model for the purpose of Reliability Mathematical Model and inherent reliability prediction.

DATA FOR COSTER MODEL

It has a specified MTBF of 1000 hours, and is expected to be used over a life period of at least 15 years. For the purpose of this analysis by COSTER, 15 years was used for the equipment's useful life.

The cost data used within the parts program were estimated values based upon respective components pricing from a commercial distributor. Specific parts costs from the prime contractor were not available, so it was necessary to make estimates on the basis of commercial pricing. The cumulative parts cost was only a fraction of the total reliability program cost.

Table A1 contains the principal parts breakdown containing the total number of parts in each class.

Using COSTER, the inherent MTBF of the equipment was calculated to be 18.02 hours, one tenth of the MTBF obtained from the basic parts failure rate data. This degradation in predicted MTBF is an inherent property of the model since the predicted reliability in terms of MTBF does not take into consideration basic workmanship errors which could cause "pattern failures" (those failures with assignable causes and consequent repetitive occurrence); the predicted reliability is based entirely on purely random failures from an exponential distribution of time to failure. The degradation of the predicted value by a factor of one-tenth has been experienced on many electronic equipments to date.

The Parts Program is to be used as a vehicle for determining the effects of both unit redundancy, and tighter screening levels within each of the parts classes. This analysis could be done as early in the system's life cycle as the draft proposed ROC (Required Operational Capability).

The Reliability Design Review, Reliability Prediction, and Failure Mode, Effects and Criticality Analysis (FMECA) were assumed to be part of the reliability program. The specific formulas for the cost and MTBF calculations

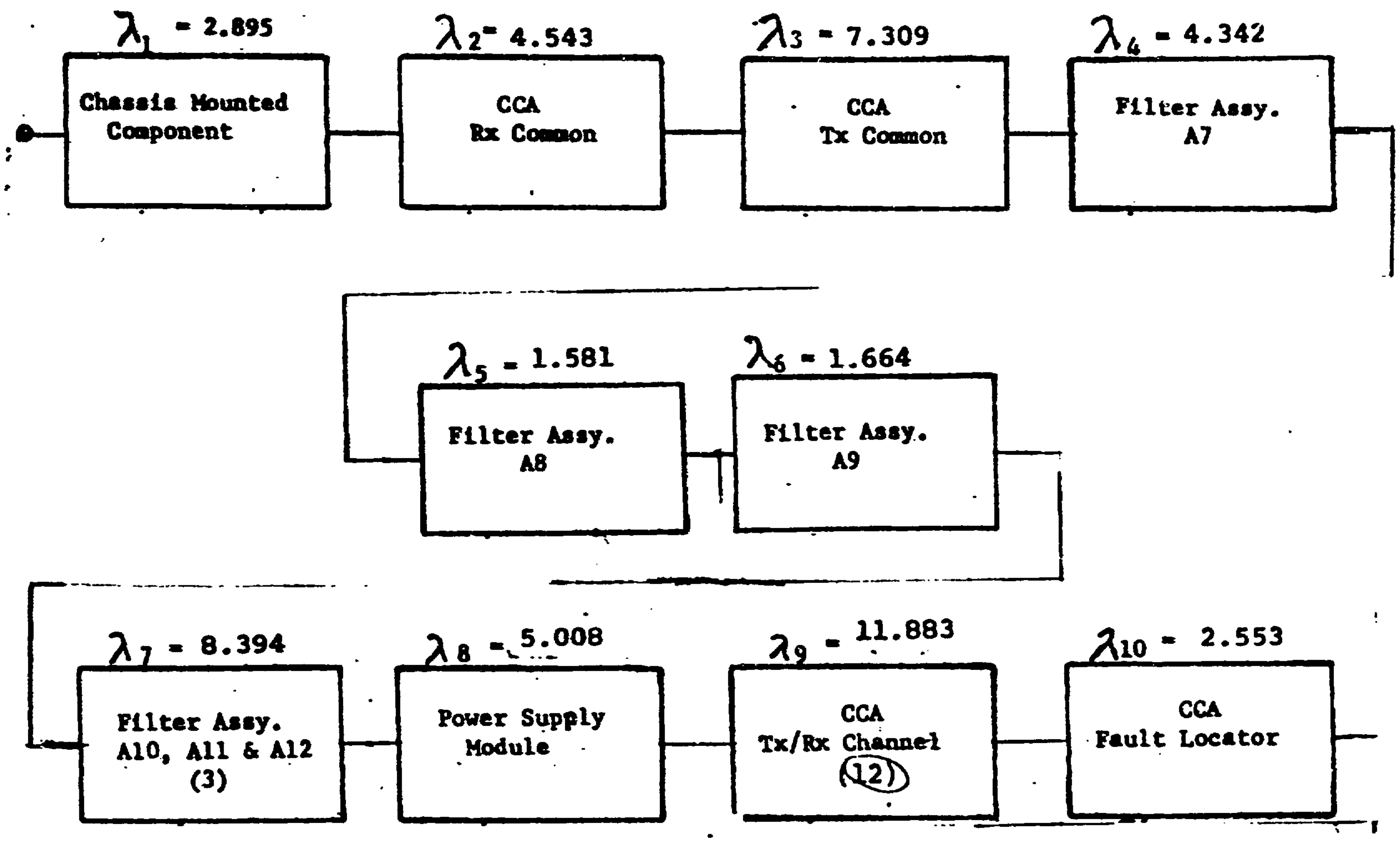


Figure A1 SERIES BLOCK DIAGRAM FOR HIGH SPEED SERIAL DATA BUFFER

TABLE A1 PARTS CLASS BREAKDOWN

PART CLASS	NUMBER
IC's (Analog)	52
IC's (Digital)	805
FET's	0
NPN's	51
PNP's	29
Diodes	178
Zener Diodes	50
MW Diodes	0
Resistors	1015
Capacitors	611
Inductors	25

were based upon a linear regression analysis on ten equipments, done by Me Mercurio and Skaggs (4). It was based upon an equipment's complexity as measured by the total number of parts, NP. However, when their empirical formulas were applied to non-avionics equipment, the resultant costs for each of the programs, Design Review, Prediction, and FMECA, were unrealistically large. An alternative technique was implemented, in which the cost of the prediction was calculated using an array of prediction costs per part for each of the basic part types and the respective number of each part type. For example, if the number of Analog Integrated Circuits was between 100 and 1000, then the reliability prediction cost per Analog IC would be read from the file RPDAT (Table A2) as $3 per part.

The MTBF improvement developed by Mercurio and Skaggs (4) was retained, and calculated in accordance with Figure A2.

PROGRAM	COST	RESULTANT MTBF
DESIGN REVIEW	$C_{DR} = (0.023/0.101)C_{RP}$ where C_{RP} is the Reliability Prediction Cost	(1.11)XBRI
RELIABILITY PREDICTION	$C = \sum_{I=1}^{NPC} \text{Number}(I)CC(I)$, where NPC is the total number of distinct part classes, Number(I) is the number within each Parts Class, and CC(I) is the cost code indicating the prediction cost per Part, as given in file RPDAT.	(1.428)(1.11)XBRI
FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS (FMECA)	$C_{FM} = (0.09/0.101)C$	(1.296)(1.428)(1.11)XBRI

Figure A2. Cost/Reliability Calculations for Design Review, Reliability Prediction and Failure Mode, Effects and Criticality Analysis

The value XBRI of Figure A2 is the MTBF prior to the reliability design review. The flow chart of Figure A3 indicates the possible value of MTBF achieved after each of the respective reliability programs. Within the computer subroutines (Appendix B), the variable XBRI was chosen for the MTBF prior to the design review, and θ was the achieved MTBF subsequent to each reliability program.

TABLE A2 RELIABILITY PREDICTION COSTS PER PART (FILE RPDAT)

Number of Respective Parts	0 100	101 1000	1001 10000	10001 100000	100001 1000000	Over 1000001
Analog IC's	6	3	1	0.2	0.05	0.02
Digital IC's	6	3	1	0.2	0.05	0.02
FET's	5	2	0.75	0.20	0.10	0.02
NPN's	5	2	0.75	0.20	0.10	0.02
PNP's	5	2	0.75	0.20	0.10	0.02
Diodes	3	1	0.50	0.25	0.03	0.001
Zener Diodes	4	1.5	0.75	0.50	0.05	0.005
MW Diodes	5	2.5	1.5	1.0	0.10	0.01
Resistors	1	0.75	0.4	0.2	0.01	0.001
Capacitors	2	1.5	0.8	0.4	0.02	0.0002
Inductors	3	1.75	1.0	0.5	0.09	0.0008

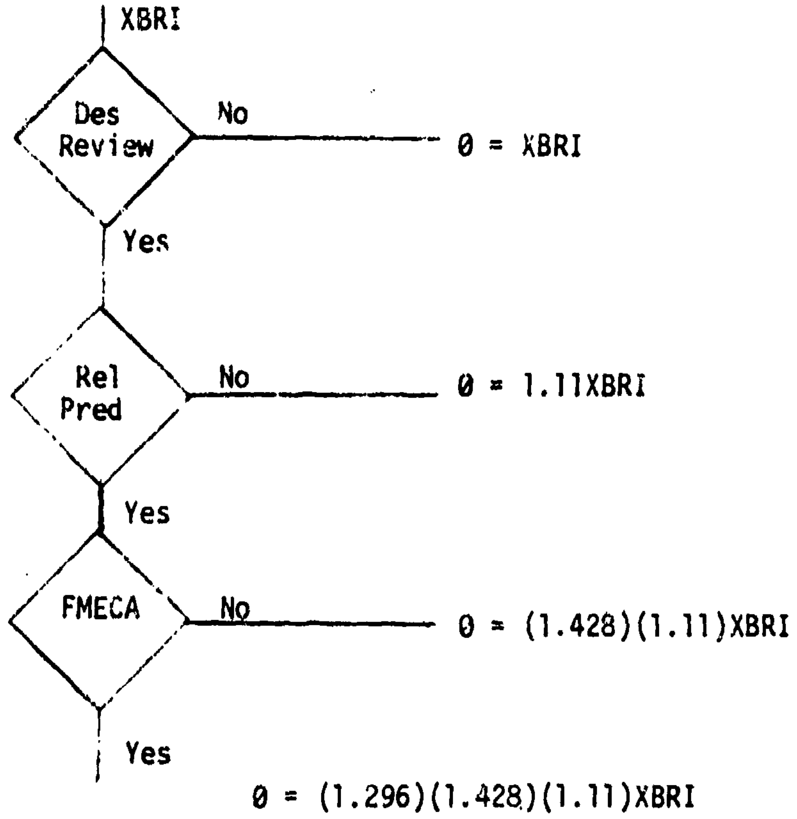


Figure A3. Flow Chart of Design Review, Prediction and FMECA Programs

As is indicated in Figure A3, the specific programs are assumed sequential i.e. a reliability prediction is permitted only if there had been a design review, and the FMECA occurs only if both the design review and prediction were performed.

The Reliability Demonstration test was to be done in accordance with MIL-STD-781, test plan XXII, having a discrimination ratio (θ_0/θ_1) of 3; furthermore, the Alpha risk (probability of rejecting equipment having a true MTBF equal to the specified MTBF, θ_0) and Beta risk (probability of accepting equipment with a true MTBF equal to the minimum acceptable MTBF, θ_1), were both equal to 10%.

With a specified MTBF of 1000 hours, the minimum acceptable value of MTBF is 333.3 hours.

Using the values prescribed for test plan XXII for both the Demonstration and Qualification Tests, results in a test duration of 3.1 θ_0, or 3100 hours, with a maximum acceptable number of failures of 5. The sample size for the test was prescribed in accordance with paragraph 4.2.3.1 of MIL-STD-781B, and determined to be twenty samples, for a lot size of 200 units.

For the Production Sampling test, which was to be run in accordance with MIL-STD-781B, plan IVa, with Alpha and Beta risks of 20% and a discrimination ratio (θ_0/θ_1) of 3.0, the accept-reject criteria was outlined in paragraph 4.2.8.4a of MIL-STD-781B, and indicated a maximum test duration of 1.50 , or 1500 hours, with the maximum acceptable number of failures of 2. The sample size of 3 was determined assuming 500 available hours to complete the production sampling test within one month. Thus the required sample size was calculated as (1000 hours)(1.5)/500 hours, or three samples. This value differs from that prescribed in Table 5 of MIL-STD-781B because it is determined mainly by the monthly production rate and the available number of hours to run the test.

The number of production sampling tests depends upon the contractor's production schedule. Assuming a production rate of 200 per month, the total production run of 4300 would be completed in 21.5 months, so there would be 22 production sampling tests, each with three samples for a lot size of 200 units.

For the example calculation presented here, the hourly testing cost for each of the Demonstration tests, Qualification tests, and Production Sampling tests was $50/hour.

Table A3 contains the specific input data for a production contract of 4300 units.

TABLE A3 SPECIFIC INPUT DATA FOR EXAMPLE PROBLEM

	Production Contract
Number of Equipments (QUANT)	4300
Specified MTBF (θ_o)	2500
Demonstration Test Duration (DT781)	3.1 θ_o = 7750
Qualification Test Duration (QT781)	3.1 θ_o = 7750
Production Sampling Test Duration (PT781)	1.5 θ_o = 3750
Maximum Acceptable Number of Failures for Demonstration Test (DKF)	5
Maximum Acceptable Number of Failures for Qualification Test(QKF)	5
Maximum Acceptable Number of Failures for Production	2
Sampling Test (PKF) Sample Size for Demonstration Test (DN)	20
Sample Size for Qualification Test (QN)	20
Sample Size for Production Sampling Test (PN)	3

TABLE A3 (Continued)

	Production Contract
Testing Cost ($/chamber hr) -- Demonstration Test (DCJ)	50
Testing Cost ($/chamber hr) -- Qualification Test (QCJ)	50
Testing Cost ($/chamber hr) -- Prod Sampling Test (PCJ)	50
Testing Cost ($/chamber hr) -- Burn-In (BCJ)	25
Minimum Burn-In Test Time (T)	48
Required Failure Free Hours During Burn-In (H)	24
Number of Equipments Per Burn-In Chamber (BN)	20
Number of Production Sampling Tests (NTST)	22
Usage Life in Years (LIFE)	15
Weekly Usage (Days/Week)	7
Daily Usage (Hrs/Day)	8
Average Repair Cost Per Equipment While Deployed(CREP)	600

OUTPUT RESULTS

COSTER was run for a production contract of 4300 units, with a specified MTBF of 1000 hours. Table A4 contains the variable input data for the reliability program.

Table A5 contains the Total Cost and Resultant MTBF when no reliability program was imposed. The base MTBF, with no screening and no parts redundancy was 18.03 hours yielding a resultant total policy cost in excess of 6 billion dollars for 4300 equipments operating over an expected life of 15 years.

Table A6 contains the results of policy 38, the optimal reliability program, yielding a total policy cost in excess of 87 million dollars with an MTBF of 1300.22 hours. The cost of implementing the optimal reliability program was 789 thousand dollars.

Table A9 contains the results of all policies, with the total costs sorted in increasing order. Because the Field Support costs greatly outweigh the reliability program costs, the optimal reliability program was the one with the largest MTBF. In general, however, this will not be true; the maximum achievable MTBF is a function of the current technology.

TABLE A4 VARIABLE INPUT DATA, θ_o = 1000 HOURS

◆◆

VARIABLE INPUT DATA

◆◆

SPECIFIED EQUIPMENT MTBF-THETA(0)	1000.00
DEMONSTRATION TEST TIME - MULTIPLE OF THETA(0)	3.10
QUALIFICATION TEST TIME - MULTIPLE OF THETA(0)	3.10
PROD SAMPLING TEST TIME - MULTIPLE OF THETA(0)	1.50
MAX ALLOWABLE FAILURES--DEMONSTRATION TEST	5
MAX ALLOWABLE FAILURES--QUALIFICATION TEST	5
MAX ALLOWABLE FAILURES--PROD SAMPLING TEST	2
NUMBER OF TEST SAMPLES--DEMONSTRATION TEST	20
NUMBER OF TEST SAMPLES--QUALIFICATION TEST	20
NUMBER OF TEST SAMPLES--PROD SAMPLING TEST	3
NUMBER OF PROD SAMPLING TESTS THROUGHOUT CONTRACT	22
TEST CHAMBER COST(PER HOUR)--DEMONSTRATION TEST	50.00
TEST CHAMBER COST(PER HOUR)--QUALIFICATION TEST	50.00
TEST CHAMBER COST(PER HOUR)--PROD SAMPLING TEST	50.00
BURNIN CHAMBER COST(PER HOUR)	25.00
MINIMUM REQUIRED BURNIN TIME(HOURS)	48.00
FAILURE FREE HOURS REQUIRED	24.00
NUMBER OF EQUIPMENTS PER BURNIN CHAMBER	20
TOTAL NUMBER OF EQUIPMENTS TO BE FIELDED	4300
EQUIPMENT EXPECTED USAGE LIFE (YEARS)	15
EXPECTED DAILY USAGE (HRS/DAY)	8
EXPECTED WEEKLY USAGE (DAYS/WEEK)	7
REPAIR COST OF SINGLE EQUIPMENT	600
THE OPERATIONAL ENVIRONMENT IS	GF
AND THE CONSEQUENT K-FACTOR IS	1.00

◆◆

TABLE A5 RESULTANT COST AND MTBF WHEN NO RELIABILITY PROGRAM IS IMPOSED

POLICY 1

---------TASK---------	-----COST-----	---RESULTANT MTBF---
NONE	0.00	18.03

TOTAL RELIABILITY COST .0

FIELD SUPPORT COST .62566739539000OE 10

TOTAL POLICY COST .62566739954E 10

RESULTANT MTBF 18.03

TABLE A6 RELIABILITY PROGRAM YIELDING THE MINIMUM TOTAL COSTS

POLICY 38

TASK	COST	RESULTANT MTBF
PARTS PROGRAM	10432.68	292.90
REL DESIGN REVIEW	1116.41	325.12
REL PREDICTION	4902.50	464.27
REL DEMO TEST	42167.89	1048.38
REL QUAL TEST	10509.26	1131.87
PROD SAMPLING TESTS	719778.32	1300.22

TOTAL RELIABILITY COST .7889060607E 06

FIELD SUPPORT COST .8677191838200000E 08

TOTAL POLICY COST .8756082444E 08

RESULTANT MTBF 1300.22

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TABLE A7 RESULTS OF ALL POLICIES WITH TOTAL COST SORTED IN INCREASING ORDER.

TOTAL COST	POLICY	MTBF	REL PROG COST	FLD SPT COST
87560824.44	38	1300.22	788906.06	86771918.38
87722243.78	78	1300.22	1049221.39	86673022.39
89913874.41	36	1265.07	730559.98	89183314.43
90072499.63	76	1265.07	990937.78	89081561.85
90296149.30	40	1260.84	813500.45	89482648.85
90454427.24	80	1260.84	1073886.00	89380541.24
90657776.65	34	1254.67	734927.27	89922849.38
90815543.72	74	1254.67	995324.20	89820219.51
92474929.59	30	1230.79	807219.76	91667709.83
92630669.62	70	1230.79	1067661.80	91563007.81
95852495.73	28	1186.29	746463.07	95106032.66
96004231.87	68	1186.29	1006993.85	94997238.02
96390982.82	32	1180.81	843535.65	95547447.17
96542204.02	72	1180.81	1104077.82	95438126.21
96955876.90	26	1172.76	752797.82	96203079.08
97106332.88	66	1172.76	1013356.88	96092976.00
99748035.52	22	1131.87	69127.74	99678907.78
99894426.94	62	1131.87	329776.23	99564650.71
103582461.28	20	1089.80	55191.27	103527270.02
103724337.29	60	1089.80	315938.54	103408398.75
104075770.69	24	1084.71	62550.45	104013220.24
104217075.37	64	1084.71	323310.17	103893765.20
104797808.09	18	1077.27	56563.79	104731244.30
104928268.13	58	1077.27	317341.91	104610926.22
107676364.30	14	1048.38	58619.48	107617744.83
107813423.19	54	1048.38	319471.45	107493951.74
113548087.52	12	994.03	45689.42	113502398.10
113678184.35	52	994.03	306691.52	113371492.84
114328465.20	16	987.29	50951.78	114277513.42
114457642.17	56	987.29	311973.60	114145668.57
115484238.10	10	977.37	46955.19	115437282.90
115612037.49	50	977.37	308006.52	115304030.97
132952550.94	39	855.14	1014255.46	131938295.48
133060588.66	79	855.14	1275723.97	131784864.69
152145066.20	37	746.75	1054825.95	151090240.24
152229782.39	77	746.75	1316772.73	150913009.66
187540040.23	8	601.69	20820.16	187519220.07
187579217.24	48	601.69	283659.07	187295558.17
191913512.89	35	591.17	1055224.82	190858288.07
191948436.39	75	591.17	1318144.36	190630292.03
195502649.83	23	577.39	89752.22	195412897.61
195531749.45	63	577.39	352781.42	195178968.03
203781056.99	31	557.24	1300265.76	202480791.23
203801068.59	71	557.24	1563464.42	202237604.17

TABLE A7 (Continued)

207877130.41	33	545.61	1078886.26	206798244.16
207891560.14	73	545.61	1342188.01	206549372.13
243015649.21	46	464.27	280605.63	242735043.39
243048994.78	6	464.27	16451.59	243032543.19
247683839.00	61	455.61	333003.50	247350835.50
247723400.83	21	455.61	68742.15	247654658.68
253125764.74	69	447.89	1516010.16	251609754.58
253171087.25	29	447.89	1251650.30	251919436.95
346903667.15	44	325.12	278025.19	346625641.96
347084075.72	4	325.12	11549.09	347072526.63
352230532.81	59	320.22	306455.04	351924077.77
352418863.40	19	320.22	39865.50	352378997.89
354109148.49	67	319.50	1388424.33	352720724.16
354298673.93	27	319.50	1121617.78	353176856.14
380633493.92	55	296.33	331988.10	380301505.82
380864998.16	15	296.33	64799.26	380800198.90
385032176.88	42	292.90	277714.31	384754462.57
385270572.01	2	292.90	10432.68	385260139.33
390923474.94	57	288.50	306153.10	390617321.84
391170991.76	17	288.50	38749.82	391132241.93
392392543.71	65	288.22	1389563.79	391002979.93
392640662.52	25	288.22	1122152.53	391518509.99
493178851.83	53	228.65	316755.61	492862096.22
493594934.95	13	228.65	47325.64	493547609.31
704104399.54	51	160.12	297413.59	703806985.95
704935871.66	11	160.12	24366.41	704911505.25
781523189.20	49	144.25	297434.80	781225754.40
782525609.52	9	144.25	23250.00	782512359.52
3042631649.05	47	37.04	273408.45	3042358240.59
3045711878.88	7	37.04	10387.48	3045701491.41
3943142806.80	45	28.58	246526.99	3942896279.81
3947235151.78	5	28.59	6018.91	3947229132.38
5620679224.20	43	20.02	222336.69	5630455887.50
5626644318.00	3	20.02	1116.41	5636643201.70
6250019275.50	41	18.03	213240.34	6249806035.20
6256673953.90	1	18.03	0.00	6256673953.90

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