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RELIABILITY TRADE-OFFS FOR UNIT PRODUCTION COST

Martin Marietta Corporation

Thomas W. Butler

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

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Martin Marietta Corporation conducted a 12 month study program to develop models for the evaluation of trade-offs in the requirement to execute specific reliability program elements, the resultant achieved reliability and the impact upon unit production cost. The program elements considered include: Parts standardization, selection and control; vendor selection, qualification and surveillance; and screening and test programs at piece part and various assembly levels.

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PREFACE

This final report was prepared by the Orlando Division of Martin Marietta Corporation for the Rome Air Development Center, Griffiss Air Force Base, New York, under Contract F30602-77-C-0118. The purpose of the contract was to study and define relationships between reliability program elements and their resultant impacts upon achieved equipment reliability and unit production costs.

This report is submitted as the input for CDRL Sequence Number A002 and covers the period from June 1977 through May 1978. The RADC Project Engineer responsible for the technical administration of this study was Mr. Jerry Lipa, Rome Air Development Center.

In addition to the author, contributors to the acquisition of data within Martin Marietta were Robert Boemler, William Long, Edwin Kimball, Donald Cottrell, Brad Olson, Jeff Bracey, Gloria Isler, and Betty Jean Thomas. Mr. Thomas Gagnier was the Program Manager.

SUMMARY

This report presents a study by Martin Marietta Corporation, Orlando, Florida, for the U. S. Air Force, Rome Air Development Center, to gather and analyze factory and field cost and reliability data on electronic equipment to develop relationships between reliability and unit production cost. Higher levels of reliability for electronic assemblies can result in substantial cost savings during operational deployment since fewer repair actions are necessary, fewer maintenance personnel required, fewer spare parts needed, etc.

Reliability assurance actions such as parts selection and control, vendor surveillance, and screening and testing programs may result in increased unit production cost and thus partially offset the reduction in life cycle cost due to fewer field failures. This study is intended to provide guidance in evaluating tradeoffs between reliability tasks that achieve the desired field reliability at lowest unit production cost.

A literature search and an industry survey have been conducted to identify programs where the study parameters could be explicitly identified. A summary of several representative programs is included to amplify the role of various reliability program elements and illustrate the variability in results between companies. The need to understand roles of the elements along with the embedded reliability discipline of each company is emphasized. Some specific incremental cost figures with the attendant reliability improvement are provided. A discussion of technique for applying this information to conceptual design phase tradeoffs is also presented in this report.

EVALUATION

1. The objective of this study was to develop relationships that would be capable of equating desired values of reliability to increments of increase in unit production cost of electronic equipment, and the determination of the benefits/impacts of reliability attributable costs, such as parts selection and control, vendor surveillance, screening, and testing (type and duration) on reliability and unit production costs. These relationships would also allow for trade-offs among parameters, such that subsequent relationships developed would allow maximum reliability to be attained at the lowest possible increase to unit production cost.

2. The methodology developed satisfactorily achieves the objectives for which it was planned. The reliability equation allows the analyst to compare the reliabilities that could be expected from different designs, growth testing programs, levels of part quality, screening methods and burn-ins, and amount and severity of limited environmental testing. It can also allow any combination of these variables above that might be different in competing reliability plans. The cost methodology developed will allow for a comparison of the associated unit production cost of the above mentioned reliability programs.

3. The methodology developed here will enable the analyst, be it program manager, design engineer, logistician, reliability engineer, or anyone else to evaluate competing reliability program options with respect to

the equipment reliability and unit production cost. These in turn will serve as inputs to life cycle cost trade-offs that are conducted early in the development of an equipment's life cycle to determine the proper structure of the reliability program and the testing that will be necessary.

JERRY F. LIPA, Jr.
Project Engineer

1.0 INTRODUCTION

1.1 Background

Both reliability and life cycle cost of avionics equipment and systems are of interest to the Air Force. It has been apparent for many years that for some additional cost increments during development, the equipment/system's life cycle cost actually is lowered by increasing the reliability of the equipment/system which, in turn, either increases or decreases unit production cost of the equipment/system. Life cycle cost consequently is lowered by a decrease in the number of failures during the equipment/system's lifetime, which in turn reduces the need for spare parts, maintenance personnel, and other repair facilities. Also, the various means of attaining a given reliability value impose different ramifications on the unit production cost of the equipment/system. While various committees and studies have been aimed at the quantification of cost of failure, little has been attempted relative to the quantification of increment in unit production cost (for different design alternatives to achieve a given reliability) versus reliability attainable. If visibility is to be provided relative to potential tradeoffs between higher initial costs and lower life cycle costs due to higher reliability, such quantification as mentioned above is a necessity.

1.2 Objective

This study intends to provide the perspective through which an engineer, either developer or user, in the early conceptual phase of design, can evaluate tradeoffs between the structure of the emerging reliability program and the resulting expectancy for unit production cost (UPC) and for subsequent field reliability. The relationships are quantified incrementally to allow the customization of a reliability program to an optimum level of cost and achieved reliability.

Specific reliability elements included in the investigation are:

1 Parts selection, standardization, and control

2 Vendor selection, qualification, and surveillance

3 Screening and testing of parts, assemblies, etc.

1.3 Approach

This study was conducted in three essentially sequential phases. The first phase was a search for sources of data, i.e., program histories, in which reliability tasks, reliability achievement, and unit product cost were explicitly indicated or could be judgmentally estimated with acceptable objectivity and accuracy. Literature search, mail survey questionnaires, and personal contact were used. Sources were contacted and relevant data exchanged to build a data base. In the second phase the data was analyzed to detect causal relationships between variables from which various production models could be synthesized. Finally, in the third phase, methods were developed for evaluation of tradeoffs that would benefit the conceptual equipment/system designer in optimizing the reliability versus unit production cost equation.

During the source identification and data gathering phase, a significant resistance was encountered to the disclosure of specific unit production cost records and to a lesser degree the disclosure of specific reliability achievement. To circumvent this obstacle, data were sometimes transmitted by interview in which relative values were discussed, allowing the source spokesmen considerable opportunity to censor results or make their own interpretations. The consensus of these discussions are quite consistent and in agreement with material extracted from the literature, and therefore are judged to be a valid contribution to the study.

2.0 DATA COLLECTION

2.1 Literature Review

A comprehensive literature review was made to obtain information and pertinent data on reliability versus cost. Martin Marietta's Technical Information Center (TIC) was researched for up-to-date information. A bibliography, constructed using key words, was formulated and reviewed for applicability. Data sources used in this computer search include Martin Marietta in-house documents and documents listed by other documentation centers, such as the Defense Documentation Center (DDC), NASA Scientific and Aerospace Reports (STAR), and National Technical Information Services (NTIS).

2.2 Data Source Contacts

Upon contract initiation, a list of potential data sources was generated from sources used in previous study contracts and from Government-Industry Data Exchange Program (GIDEP) memberships. Other suggested sources resulted from consultation with RADC. The data survey letter was mailed to 260 companies and agencies, and about 50 companies answered. Every survey sheet returned was reviewed carefully to determine whether the data would be useful in this study. Each respondent to the survey was contacted by telephone to further detail the amount and type of reliability information available. Of the survey questionnaires returned, 25 respondents indicated that they had no data applicable to the study and 5 indicated that such data would be strictly proprietary. From the remaining number who indicated that they did have reliability versus cost data, the validity and timeliness for this study varied widely, from good to unusable. A list of those companies who either provide data directly or who gave their time to enter into contributory discussions on the subject is included in the Appendix.

2.3 Description of Reliability Elements

A comprehensive reliability program is composed of many tasks and imposes many requirements that impact upon cost elements in all phases of the product life cycle. While it is the objective of this study to focus upon the production phase, it is widely acknowledged that unit production cost can be significantly influenced by decisions made during the design phase as well. The reliability elements for which cost relationships have been collected in this report are described in some detail.

Parts Selection, Standardization, and Control

Parts selection as a reliability element can impact both nonrecurring and recurring costs. Each aerospace contractor that has had previous program experience with contractual application of parts standardization or parts controlling specifications such as MIL-STD-454, will have some form of preferred parts list supplemented with reliability values and cost quotations to assist the design engineer in evaluating design tradeoffs. Several secondary cost and reliability benefits are realized by selecting parts exclusively from this list. They include:

1 Part reliability/quality is firmly established.

2 Parts are readily available from company stockrooms, vendors/ distributors, and military depots (for repair).

3 Price is controlled by strong competition.

4 Drawings, specifications, test procedures, etc., already exist, resulting in minimum cost for documentation.

5 Minimum cost to handle results from ordering in greater quantities, ordering and expediting fewer types, and having fewer

setups for test and inspection, fewer stock bins, and simplified inventory control.

When designers deviate from the preferred parts list, both nonrecurring engineering and recurring production costs escalate sharply as implied by the list of standardization benefits. The percentage of preferred parts on the bill of materials is a good figure-of-merit to key upon when attempting to measure the reliability and cost awareness of the design engineering group.

Beyond parts standardization, the designer has two other prime responsibilities in parts selection. Foremost is to select parts that can withstand all combinations of electrical, thermal, and structural exposure without becoming overstressed, and secondly is to select the appropriate quality levels, e.g., JANTX, and ER, to meet the specified reliability.

Vendor Surveillance

Selecting good vendors and maintaining surveillance of the quality of their product is essential to controlling production costs and schedules. Assuming that each vendor has been previously screened by a facility survey and that his product has been tested and qualified, the most common mode of continuing surveillance is by incoming inspection. This may entail testing a small quantity (sample) of each shipment received, or more thorough inspection varying to an extreme where each functional parameter is carefully measured under extreme environmental conditions for each part received.

When parts fail the incoming inspection in excessive numbers, it is assumed that a problem exists that is potentially detrimental to the quality of all parts, and it is essential to collaborate with the vendor to determine the cause and to devise corrective action. Occasionally, it is beneficial to conduct the inspections at the vendor's facility using his equipment. The ultimate in vendor surveillance is to captivate his production process and constantly monitor all activities.

Often the vendor of specialty items has neither the extensive facilities nor the knowledge to handle analysis of exotic failure mechanisms. In these situations the customer may have to provide the resources necessary to assist and/or train the vendor in solving the problem and obtaining positive corrective action.

Screening and Testing

Testing herein refers to the measurement of functional performance and is usually qualified as to the conditions prevailing during the test. Screening refers to the operation of a part, assembly, or system when a stress is imposed that is nondestructive to a reliable part but will likely precipitate the failure of an improperly constructed unit. Testing is combined with screening before and after failure, to determine when the failure has occurred. Testing sometimes can be conducted continuously during screening to better determine the exact time of failure.

The following types of screening exercises are addressed in this study:

1 Burn-in

2 Temperature extremes

3 Temperature cycles

4 Sinusoidal vibration

5 Random vibration

6 Mechanical shock.

Burn-in commonly is combined with other screening stresses such as temperature cycling, and with testing, to compress the processing time required to precipitate the failure of any marginal components or assemblies. Often a failure-free burn-in period is specified for each production assembly.

Failure-free burn-in or other failure-free screening, especially the combination of random vibration with temperature cycling, has been shown to be very effective in precipitating early life failures due to production workmanship or material defects. Typically, several cycles of this environmental exposure are required during which failures are detected and repaired. When this is followed with two or more cycles without failure, it is assumed that all infant mortality defects have been detected and that the inherent design reliability has been achieved.

Reliability growth testing prior to the full scale production phase is important. Otherwise failures will continue to occur during screening at an unacceptable frequency. Growth testing of new designs provides a period of observation during which inadequate design margin, circuit instabilities, thermal runaway, and other problems not detectable by paper analysis are discovered and corrected. While the cost of these tests is primarily nonrecurring engineering, the failure to achieve adequate reliability growth will result in markedly higher production costs for excessive troubleshooting and repair of design problems. Even more costly is the situation where these design problems cause repeated operational failures after delivery to the user.

2.4 Programs Investigated

At the conclusion of the data search and acquisition phase, a summary and review of significant information gathered indicated that the 14 programs described below would form the basis for further study.

Because of the tendency toward proprietary treatment of production cost, the programs are identified by generic names and cost figures are treated in relative terms. Whenever labor data was received in terms of dollars, it was converted into manhours at an estimated rate for the time the tasks were active. When material costs are indicated, they may be assumed to be 1975 constant dollars.

The 14 programs studied are as follows:

Guided Projectile Parts Program
Target Identification Set Detector
Tactical Missile
Antiballistic Missile Parts Program
Inertial Navigation Set I
Inertial Navigation Set II
Inertial Navigation Set III
Satellite Communications
Performance Monitor System
Multiplex Set
Automatic Test Equipment
Inertial Sensor Unit
Guided Projectile Limited Environmental Tests (LET)
Missile Autopilot LET

Guided Projectile

The guided projectile program is an Army development with a requirement for Design to Unit Production Cost (DTUPC). It provides a good study because a reliability cost tradeoff model was developed to define the relationship of desired values of reliability to increments of unit production cost. The model was used to determine the optimum cost benefits of such reliability factors as the grade of electronic parts, vendor surveillance, screening, limited environmental testing (LET), manufacturing fallout, and field failure rates.

This model was developed to provide DTUPC estimates for the projectile baseline configuration and to compare the cost and reliability of this configuration with other candidate configurations. Alternates were identified as cost effective, lowest cost, or highest reliability configurations. The study assessed all electronic components except LSI, hybrid, and magnetic devices and included over 80 part types with a total usage of 679 parts. The use of the model is demonstrated by an example from the guided projectile program.

The DTUPC costs were estimated for production buys of 8,400 and 124,000, and considered the following costs:

1 Purchased material recurring costs
  a Material purchase price - lowest quote from responding suppliers for each device
  b General and administrative (G&A) expenses
  c Fee
  d Fallout factor - estimate of percent failure (fallout) of each device after receipt (includes in-house screening, where applicable, and manufacturing and test operations).

2 Dedicated facility recurring costs
  a Manufacturing, quality, and engineering labor
  b G&A
  c Overhead
  d Fee.

The baseline reliability used for the study was 0.824 at the end of 10 years storage. For each alternate candidate device, changes to the system cost (ΔC) and system reliability (ΔR) were calculated. Reliability calculations were based on the quality grade of the purchased part and the extent of any additional in-house environmental screening.

The model for cost calculations was developed as follows:

$$C = N\,(1 + G\&A)\,(1 + Fee)\,[(1 + F)\,C_p + (1 + OH)\,(CTL + RI + Mfg)]$$

$$C = N\,[1.1387\,(1 + F)\,(C_p) + 2.69737\,(CTL + RI + Mfg)]^*$$

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*Prevailing 1975 Martin Marietta rates used in this example.

where

N = part quantity per projectile

F = fallout factor

C_p = device purchase price

CTL = Component Test Laboratory (CTL) in-house screening labor

RI = receiving inspection labor

Mfg = manufacturing labor.

Using this model, component costs for the baseline devices and all alternate candidates were calculated. These costs were then totaled to get the baseline system, a lowest-cost system, a highest-reliability system, and a cost-effective system (the combination which resulted in the highest reliability for the least cost). Two factors not considered at the beginning of this study were included for improved accuracy and completeness:

1 The effect of adding the cost of manufacturing rework to the cost model

2 The effect of having plastic encapsulated integrated circuits (ICs) screened by the supplier to the equivalent of MIL-STD-883 Class B rather than by Martin Marietta.

The guided projectile generation breakdown established the baseline parts for the study. Alternative candidates for each baseline part were also identified. Table 1 is a partial list of the baseline parts and alternates for semiconductor devices. The baseline part is identified by the digit zero in the XX.0 of the first column, and the alternate candidates are identified by the digits 1, 2, 3, etc., in the same column.

In this study, 87 baseline parts and over 250 alternates were evaluated. Criteria for evaluating candidates included:

1 Value of projectiles saved $\geq$ resultant cost increase

2 System DTUPC and reliability values attained

3 Schema: accept/reject by case as shown in Figure 1

4 Derivation of case accept/reject

a Case I, $+\Delta R$ and $+\Delta C$. An "investigate slope" region. Value projectiles saved $\geq$ resultant cost increase [$+\Delta R_X$ (DTUPC) $\geq +\Delta C_X$].

$$\frac{+\Delta R_X}{+\Delta C_X} \geq \frac{1}{\text{DTUPC}} \geq \frac{1}{\$3564} \geq 0.000280/\$$$

b Case II, $+\Delta R$ and $-\Delta C$. An "always accept" region. If two or more alternate candidates are in this region, generally select the one with the largest cost saving, i.e., largest $-\Delta C$.

c Case III, $-\Delta R$ and $+\Delta C$. An "always reject" region.

d Case IV, $-\Delta R$ and $-\Delta C$. An "investigate slope" region. Value projectiles lost $\leq$ resultant cost decrease.

$$\frac{-\Delta R_X}{-\Delta C_X} \leq \frac{1}{\text{DTUPC}} \leq \frac{1}{\$3564} \leq 0.000280/\$$$

5 All reliability and cost values for ΔR and ΔC are system values so that system impacts may be directly calculated by adding to, or subtracting from, the baseline system values.

Examples of actual worksheets used in the reliability tradeoffs for unit production cost are shown in Tables 2 through 4.

Due to the screening and packaging options available, ICs fell into two basic groups for the purposes of the cost-effectiveness study. Group A consisted of the ICs that were currently only available in a ceramic DIP or TO type package (i.e., they were not available in a plastic DIP configuration). Group B consisted of ICs that were available in a plastic DIP package.

TABLE 1. Semiconductors and Potential Alternates

No.	Part Number	Quantity/ System (N)	Configuration	Testing/Lead
*1.0	SDG20110	Deleted	P DIP	Mil Temp Range**
1.1	SDG20110/883B	Deleted	P DIP	883B
1.2	SDG20110/883A	Deleted	P DIP	883A
1.3	DS201AP-2	Deleted	C DIP	883B
1.4	DG201AP-1	Deleted	C DIP	883A
1.5	DG201AA-2	Deleted	TO-99	883B
1.6	DG201AA-1	Deleted	TO-99	883A
1.7	SDG20110	Deleted	P DIP	Vendor Screened
*2.0	LM101AH/883B	8	TO-99	883B
2.1	LM101AH/883A	8	TO-99	883A
2.2	JM38510/10103BGC	8	TO-99	883B (Mil Part)
*3.0	LM108AH/883B	Deleted	TO-99	883B
3.1	LM108AH/883A	Deleted	TO-99	883A
3.2	JM38510/10104BGC	Deleted	TO-99	883B (Mil Part)
*4.0	LM109K-5/883B	1	TO-3	883B
4.1	LM109K-5/883A	1	TO-3	883A
*5.0	LM120K-15/883B	1	TO-3	883B
5.1	LM120K-15/883A	1	TO-3	883A
*6.0	LM111H/883B	1	TO-99	883B
6.1	LM111H/883A	1	TO-99	883A
*7.0	723HMQB	1	TO-99	883B
7.1	723HMQA	1	TO-99	883A
7.2	JM38510/10201BIA	1	TO-100	883B (Mil Part)
*8.0	7815KMQB	1	TO-3	883B
8.1	7815KMQA	1	TO-3	883A
*9.0	747HMQB	8	TO-99	883B
9.1	747HMQA	8	TO-99	883A
9.2	747DMQB	8	C DIP	883B
9.3	747DMQA	8	C DIP	883A
9.4	JM38510/10102BIA	8	TO-100	883B (Mil Part)
9.5	JM38510/10102BCB	8	C DIP	883B (Mil Part)
*10.0	MC1414L	Deleted	C DIP	-55 to +125°C**
10.1	MC1414BCBS	Deleted	C DIP	883B
10.2	MC1414ACBS	Deleted	C DIP	883A
*11.0	MC1563B5BS	1	TO-100	883B
11.1	MC1563A5BS	1	TO-100	883A
*12.0	MC12061P	1	P DIP	0 to 70°C**
12.1	MC12061DF[illegible]	1	C DIP	883B
12.2	MC12061P	1	P DIP	Vendor screened

*Baseline configuration
**Screen to 883B or equivalent at Martin Marietta

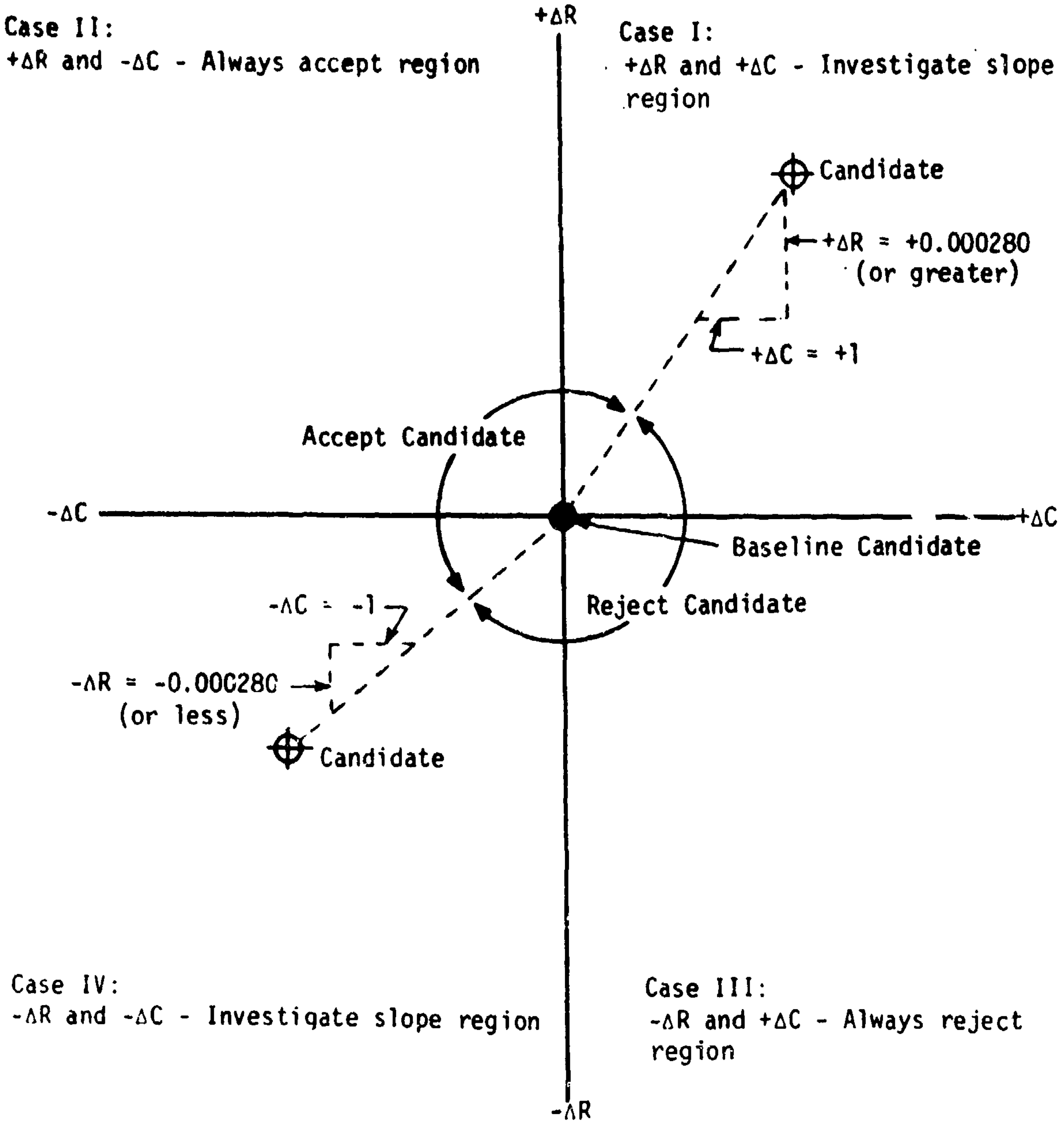

Figure 1. Cost and Reliability Acceptance Criteria

TABLE 2. ΔR Derivation (List of Current Semiconductors and Potential Alternates)

No.	Part Number	N Qty/Sys	Config.	Testing		Part λ_{nd} (N) (FITS)	Total Part Contribution To System Reliability	Δ Reliability
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
*12.0	MC12061P	1	P.Dip	0 to 70°C	0.0707	14	0.998774	-
12.1	MC12561DEDS	1	C.Dip	883B	0.0401	7	0.999387	+0.000613
*13.0	MC14528CP	1	P.Dip	0 to 70°C	0.0707	14	0.998774	-
13.1	MC14528AL	1	C.Dip	-55°C to +125°C	0.0976	7	0.999387	+0.000613
13.2	MC14528CL	1	C.Dip	-40°C to +85°C	0.0976	7	0.999387	+0.000613
13.3	MC14528AL/883B	1	C.Dip	883B	0.0401	7	0.999387	+0.000613
13.4	MC14528AL/883A	1	C.Dip	883A	0.002	2	0.999825	+0.001051
13.5	MC14528CL/883B	1	C.Dip	883B	0.0401	7	0.999387	+0.000613
13.6	MC14528CL/883A	1	C.Dip	883A	0.002	2	0.999825	+0.001051
*14.0	CD4001AE	12	P.Dip	-40 to +85°C	0.0707	48	0.995804	-
14.1	CD4001AD	12	C.Dip	-55 to +125°C	0.0976	24	0.997900	+0.002096
14.2	CD4001AD/3	12	C.Dip	883B	0.0401	24	0.997900	+0.002096
14.3	CD4001AD/1	12	C.Dip	883A	0.002	12	0.998949	+0.003145
14.4	JM38510/05202BCB	12	C.Dip	883B (Mil Part)	0.002	12	0.998949	+0.003145
*15.0	CD4011AE	13	P.Dip	-40 to +85°C	0.0707	52	0.995455	-
15.1	CD40011AD	13	C.Dip	-55 to +125°C	0.0976	26	0.997725	+0.002270
15.2	CD40011AD/3	13	C.Dip	883B	0.0401	26	0.997725	+0.002270
15.3	CD40011AD/1	13	C.Dip	883A	0.002	13	0.998862	+0.003407
15.4	JM38510/05001BCB	13	C.Dip	883B (Mil Part)	0.002	13	0.998862	+0.003407
*16.0	CD4013AE	3	P.Dip	-40°C to +85°C	0.0707	12	0.998949	-
16.1	CD4013AD	3	C.Dip	-55°C to +125°C	0.0976	6	0.999475	+0.000526
16.2	CD4013AD/3	3	C.Dip	883B	0.0401	6	0.999475	+0.000526
16.3	CD4013AD/1	3	C.Dip	883A	0.002	3	0.999737	+0.000788
16.4	JM38510/05101BCB	3	C.Dip	883B (Mil Part)	0.002	3	0.999737	+0.000788
*17.0	CD4017AE	4	P.Dip	-40 to +85°C	0.0707	16	0.998599	-
17.1	CD4017AD	4	C.Dip	-55°C to +125°C	0.0976	8	0.999299	+0.000700
17.2	CD4017AD/3	4	C.Dip	883B	0.0401	8	0.999299	+0.000700
17.3	CD4017AD/1	4	C.Dip	883A	0.002	4	0.999650	+0.001051
17.4	JM38510/05661BCB	4	C.Dip	883B (Mil Part)	0.002	4	0.999650	+0.001051
*18.0	CD4019AE	1	P.Dip	-40 to +85°C	0.0707	4	0.999650	-
18.1	CD4019AD	1	C.Dip	-55°C to +125°C	0.0976	2	0.999825	+0.000175
18.2	CD4019AD/3	1	C.Dip	883B	0.0401	2	0.999825	+0.000175
18.3	CD4019AD/1	1	C.Dip	883A	0.002	1	0.999912	+0.000262
18.4	JM38510/05302BCB	1	C.Dip	883B (Mil Part)	0.002	1	0.999912	+0.000262
*19.0	CD4023AE	1	P.Dip	-40°C to +85°C	0.0707	4	0.999650	-
19.1	CD4023AD	1	C.Dip	-55°C to +125°C	0.0976	2	0.999825	+0.000175
19.2	CD4023AD/3	1	C.Dip	883B	0.0401	2	0.999825	+0.000175
19.3	CD4023AD/1	1	C.Dip	883A	0.002	1	0.999912	+0.000262
19.4	JM38510/05003BCB	1	C.Dip	883B (Mil Part)	0.002	1	0.999912	+0.000262

FITS - Failures/10^9 hours

TABLE 3. ΔC Derivation (124,000 Production)
(List of Current Semiconductors and Potential Alternates)

No.	Part Number	N Qty/Sys	Config	Testing	K_1	(1+F) Fallout Factor	C_p Purchase Cost	Burdened Material (6)(7)(8)	K_2	Component Test Lab Labor	Receiving Inspection Labor	Mfg. Labor	Burdened Labor (10)(11+12+13)	Total Part Contribution To System Cost (3)(9+14)	Δ Cost
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
*12.0	MC12061P	1	P.Dip	0 to 70°C	1.3871	1.0707	1.35	2.0037	2.69737	0.569	0.0724	0.0062	1.7468	3.7505	-
12.1	MC12561DEBS	1	C.Dip	883B	1.3871	1.0401	5.50	7.9350	2.69737	-	0.0362	0.0062	0.1144	8.0494	+4.2989
*13.0	MC14528CP	1	P.Dip	0 to 70°C	1.3871	1.0707	0.65	0.9654	2.69737	0.569	0.0724	0.0062	1.7468	2.7122	-
13.1	MC14528AL	1	C.Dip	-55°C to +125°C	1.3871	1.0976	0.98	1.4920	2.69737	0.666	0.0724	0.0062	2.0085	3.5005	+0.7883
13.2	MC14528CL	1	C.Dip	-40°C to +85°C	1.3871	1.0976	0.85	1.2941	2.69737	0.666	0.0724	0.0062	2.0085	3.3026	+0.5904
13.3	MC14528AL/883B	1	C.Dip	883B	1.3871	1.0401	2.38	3.4337	2.69737	-	0.0362	0.0062	0.1144	3.5481	+0.8359
13.4	MC14528AL/883A	1	C.Dip	883A	1.3871	1.0020	No Bid		2.69737	-	0.0362	0.0062	0.1144	-	
13.5	MC14528CL/883B	1	C.Dip	883B	1.3871	1.0401	No Bid		2.69737	-	0.0362	0.0062	0.1144	-	
13.6	MC14528CL/883A	1	C.Dip	883A	1.3871	1.0020	No Bid		2.69737	-	0.0362	0.0062	0.1144	-	
*14.0	CD4001AE	12	P.Dip	-40 to +85°C	1.3871	1.0707	0.12	0.1782	2.69737	0.569	0.0724	0.0062	1.7468	23.1000	-
14.1	CD4001AD	12	C.Dip	-55 to +125°C	1.3871	1.0946	0.22	0.3340	2.69737	0.666	0.0724	0.0062	2.0085	28.1100	+ 5.0100
14.2	CD4001AD/3	12	C.Dip	883B	1.3871	1.0401	0.54	0.7791	2.69737	-	0.0362	0.0062	0.1144	10.7220	-12.3780
14.3	CD4001AD/1	12	C.Dip	883A	1.3871	1.0020	1.50	2.0848	2.69737	-	0.0362	0.0062	0.1144	26.3904	+ 3.2904
14.4	JM38510/05202BCB	12	C.Dip	883B (Mil Part)	1.3871	1.0020	2.04	2.8353	2.69737	-	0.0362	0.0062	0.1144	35.3964	+12.2964
*15.0	CD4011AE	13	P.Dip	-40 to +85°C	1.3871	1.0707	0.12	0.1782	2.69737	0.569	0.0724	0.0062	1.7468	25.0250	-
15.1	CD40011AD	13	C.Dip	-55 to +125°C	1.3871	1.0946	0.22	0.3340	2.69737	0.666	0.0724	0.0062	2.0085	20.4525	+ 5.4275
15.2	CD40011AD/3	13	C.Dip	883B	1.3871	1.0401	0.54	0.7791	2.69737	-	0.0362	0.0062	0.1144	11.6155	-13.4095
15.3	CD40011AD/1	13	C.Dip	883A	1.3871	1.0020	1.50	2.0848	2.69737	-	0.0362	0.0062	0.1144	28.5896	+ 3.5646
15.4	JM38510/05001BCB	13	C.Dip	883B (Mil Part)	1.3871	1.0020	2.04	2.8353	2.69737	-	0.0362	0.0062	0.1144	38.3461	+13.3211
*16.0	CD4013AE	3	P.Dip	-40°C to +85°C	1.3871	1.0707	0.20	0.2970	2.69737	0.569	0.0724	0.0062	1.7468	6.1314	-
16.1	CD4013AD	3	C.Dip	-55°C to +125°C	1.3871	1.0946	0.35	0.5314	2.69737	0.666	0.0724	0.0062	2.0085	7.6197	+1.4883
16.2	CD4013AD/3	3	C.Dip	883B	1.3871	1.0401	0.90	1.2985	2.69737	-	0.0362	0.0062	0.1144	4.2387	-1.8627
16.3	CD4013AD/1	3	C.Dip	883A	1.3871	1.0020	1.95	2.7103	2.69737	-	0.0362	0.0062	0.1144	8.4741	+2.3427
16.4	JM38510/05101BCB	3	C.Dip	883B (Mil Part)	1.3871	1.0020	3.39	4.7117	2.69737	-	0.0362	0.0062	0.1144	14.4783	+8.3469
*17.0	CD4017AE	4	P.Dip	-40 to +85°C	1.3871	1.0707	0.26	0.3861	2.69737	0.569	0.0724	0.0062	1.7468	8.5316	-
17.1	CD4017AD	4	C.Dip	-55°C to +125°C	1.3871	1.0946	0.70	1.0628	2.69737	0.666	0.0724	0.0062	2.0085	12.2852	+ 3.7536
17.2	CD4017AD/3	4	C.Dip	883B	1.3871	1.0401	1.50	2.1641	2.69737	-	0.0362	0.0062	0.1144	9.1140	+ 0.5824
17.3	CD4017AD/1	4	C.Dip	883A	1.3871	1.0020	2.70	3.7527	2.69737	-	0.0362	0.0062	0.1144	15.4684	+ 6.9368
17.4	JM38510/05661BCB	4	C.Dip	883B (Mil Part)	1.3871	1.0020	6.31	8.7701	2.69737	-	0.0362	0.0062	0.1144	35.5380	+27.0064
*18.0	CD4019AE	1	P.Dip	-40 to +85°C	1.3871	1.0707	0.20	0.2970	2.69737	0.569	0.0724	0.0062	1.7468	2.0438	-
18.1	CD4019AD	1	C.Dip	-55°C to +125°C	1.3871	1.0946	0.44	0.6681	2.69737	0.666	0.0724	0.0062	2.0085	2.6766	+0.6328
18.2	CD4019AD/3	1	C.Dip	883B	1.3871	1.0401	0.90	1.2985	2.69737	-	0.0362	0.0062	0.1144	1.4129	-0.6309
18.3	CD4019AD/1	1	C.Dip	883A	1.3871	1.0020	2.70	4.0925	2.69737	-	0.0362	0.0062	0.1144	4.2069	+2.1631
18.4	JM38510/05302BCB	1	C.Dip	883B (Mil Part)	1.3871	1.0020	3.60	5.0035	2.69737	-	0.0362	0.0062	0.1144	5.1179	+3.0741
*19.0	CD4023AE	1	P.Dip	-40°C to +85°C	1.3871	1.0707	0.12	0.1782	2.69737	0.569	0.0724	0.0062	1.7468	1.9250	-
19.1	CD4023AD	1	C.Dip	-55°C to +125°C	1.3871	1.0946	0.22	0.3340	2.69737	0.666	0.0724	0.0062	2.0085	2.3425	+0.4175
19.2	CD4023AD/3	1	C.Dip	883B	1.3871	1.0401	0.54	0.7791	2.69737	-	0.0362	0.0062	0.1144	0.8935	-1.0315
19.3	CD4023AD/1	1	C.Dip	883A	1.3871	1.0020	1.50	2.0848	2.69737	-	0.0362	0.0062	0.1144	2.1992	+0.2742
19.4	JM38510/05003BCB	1	C.Dip	883B (Mil Part)	1.3871	1.0020	2.04	2.8353	2.69737	-	0.0362	0.0062	0.1144	2.9497	+1.0247

TABLE 4. Candidate Rank (124,000 Production)
(List of Current Semiconductors and Potential Alternates)

No.	Part Number	Qty/Sys	Config.	Testing	Rank	Δ Reliability	Δ Cost	ΔR/ΔC (7) ÷ (8)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
*12.0	MC12061P	1	P.Dip	0 to 70°C	1	-	-	-
12.1	MC12561DEDS	1	C.Dip	883B	2	+0.000613	+3.2357	0.000189
*13.0	MC14528CP	1	P.Dip	0 to 70°C	4	-	-	-
13.1	MC14528AL	1	C.Dip	-55°C to +125°C	3	+0.000613	+0.6941	0.000883
13.2	MC14528CL	1	C.Dip	-40°C to +85°C	2	+0.000613	+0.5316	0.001153
13.3	MC14528AL/883B	1	C.Dip	883B	1	+0.000613	+0.3939	0.001556
13.4	MC14528AL/883A	1	C.Dip	883A		+0.001050	-	0.000
13.5	MC14528CL/883B	1	C.Dip	883B		+0.000613	-	0.000
13.6	MC14528CL/883A	1	C.Dip	883A		+0.001051	-	0.000
*14.0	CD4001AE	8	P.Dip	-40 to +85°C	5	-	-	-
14.1	CD4001AD	8	C.Dip	-55 to +125°C	4	+0.001398	+3.1229	0.000448
14.2	CD4001AD/3	8	C.Dip	883B	1	+0.001398	-9.1132	±0.000153
14.3	CD4001AD/1	8	C.Dip	883A	2	+0.002098	-0.5379	±0.003900
14.4	JM38510/05202BCB	8	C.Dip	883B (Mil Part)	3	+0.002098	+4.3911	0.000478
*15.0	CD4011AE	4	P.Dip	-40 to +85°C	5	-	-	-
15.1	CD40011AD	4	C.Dip	-55 to +125°C	4	+0.000700	+1.5615	0.000448
15.2	CD40011AD/3	4	C.Dip	883B	1	+0.000700	-4.5566	±0.000154
15.3	CD40011AD/1	4	C.Dip	883A	2	+0.001051	-0.2690	±0.000283
15.4	JM38510/05001BCB	4	C.Dip	883B (Mil Part)	3	+0.001051	+2.1956	0.000479
*16.0	CD4013AE	3	P.Dip	-40°C to +85°C	4	-	-	-
16.1	CD4013AD	3	C.Dip	-55°C to +125°C	3	+0.000526	+1.3659	0.000385
16.2	CD4013AD/3	3	C.Dip	883B	1	+0.000526	-2.4309	±0.000216
16.3	CD4013AD/1	3	C.Dip	883A	2	+0.000788	+1.0460	0.000753
16.4	JM38510/05101BCB	3	C.Dip	883B (Mil Part)	5	+0.000788	+5.9750	0.000132
*17.0	CD4017AE	4	P.Dip	-40 to +85°C	2	-	-	-
17.1	CD4017AD	4	C.Dip	-55°C to +125°C	4	+0.000700	+3.2783	0.000214
17.2	CD4017AD/3	4	C.Dip	883B	1	+0.000700	-0.6914	±0.001012
17.3	CD4017AD/1	4	C.Dip	883A	3	+0.001051	+4.5250	0.000232
17.4	JM38510/05661BCB	4	C.Dip	883B (Mil Part)	5	+0.001051	+21.0007	0.000050
*18.0	CD4019AE	1	P.Dip	-40° to + 85°C	3	-	-	-
18.1	CD4019AD	1	C.Dip	-55°C to +125°C	2	+0.000175	+0.5678	0.000308
18.2	CD4019AD/3	1	C.Dip	883B	1	+0.000175	-0.8103	±0.000216
18.3	CD4019AD/1	1	C.Dip	883A	4	+0.000262	+1.2044	0.000218
18.4	JM38510/05302BCB	1	C.Dip	883B (Mil Part)	5	+0.000262	+2.2313	0.000117
*19.0	CD4023AE	1	P.Dip	-40°C to +85°C	5	-	-	-
19.1	CD4023AD	1	C.Dip	-55°C to +125°C	4	+0.000175	+0.3904	0.000448
19.2	CD4023AD/3	1	C.Dip	883B	1	+0.000175	-1.1391	±0.000154
19.3	CD4023AD/1	1	C.Dip	883A	2	+0.000262	0.0672	±0.003899
19.4	JM38510/05003BCB	1	C.Dip	883B (Mil Part)	3	+0.000262	+0.4589	0.000571

The Group A ICs were TO-3, TO-99, TO-100, or ceramic DIP configurations and were screened to MIL-STD-882, Class B. Baselines 4.0, 5.0, 6.0, 8.0, 9.0, and 11.0 were found to be the most cost effective within their groupings. Alternate candidates 2.1 and 7.1 that were screened to level A were slightly more cost effective than their respective baselines screened to Class B. Because it would cost approximately $9 per round to incorporate these two alternates, no changes from the baseline candidates 2.0 and 7.0 were recommended.

The Group B ICs were plastic-encapsulated (voidless) configurations. The voidless construction was a "cannon hardening" requirement and provided maximum structural support to the substrate and eliminated "flying" leads.

The plastic baseline devices were purchased from the vendor as produced. Each plastic-encapsulated IC was to be judiciously screened at Martin Marietta to the equivalent of MIL-STD-883, Class B. Because the major IC vendors informed Martin Marietta during the course of the cost-effectiveness study that they would provide plastic ICs screened to this level, the screening cost was added as a variable to the study.

Both the plastic-encapsulated IC devices (vendor screened to the equivalent of MIL-STD-882 Class B) and ceramic DIP IC devices (vendor screened to MIL-STD-883 Class B) were found to be more cost effective than the baseline candidates to be screened by Martin Marietta Corporation at its Orlando Division. The results of the trade study are shown in Table 5.

Use of plastic-encapsulated DIP devices (vendor screened to MIL-STD-883, Class B) would result in no change to the tactical projectile system reliability and would permit a significant decrease in the DTUPC of \$73.20 or \$66.34 per round, depending on the production quantity.

The recommended cost beneficial changes resulting from exercising the trade-off model are shown in Table 6.

TABLE 5. Group B Findings

IC Baseline Description	Cost-Effective Alternate Candidate	8400 Production		124,000 Production	
		Projectile		Projectile	
		ΔR	ΔC	ΔR	ΔC
Plastic DIP Screened at Martin Marietta	Ceramic DIP Screened at Vendor	+0.0125	-27.90	+0.0125	-28.20
Plastic DIP Screened at Martin Marietta	Plastic DIP Screened at Vendor	None	-73.20	None	-66.34
Notes: ΔR given in 10 year system reliability values ΔC given in DTUPC system cost (1975 dollars)					

TABLE 6. Summary of Recommendations

Baseline Description	Cost-Effective Alternate Description	8400 Production Quantity		124,000 Production Quantity	
		ΔR	ΔC	ΔR	ΔC
Resistor (RNC55 and RNC60)	Resistor (CCXXXF)	None	-$16.10	None	-$14.29
Capacitor (M39014 - Level "L")	Capacitor (San Fernando)	-0.0027	- 36.35	-0.0027	- 34.67
Capacitor (CMR - Level "L")	Capacitor (CMR - Level "P")	+0.0021	+ 4.86	+0.0021	+ 4.86
Capacitor (M83421 - Level "M")	Capacitor (M83421 - Level "R")	+0.0031	+ 0.66	+0.0031	+ 0.86
Diode (JAN 1N3600)	Diode (JAN 1N4150)	None	- 0.87	None	- 0.86
Transistors (JAN)	Transistors (JANTX)	+0.0053	+ 3.99	+0.0053	+ 4.00
Plastic ICs (Screen In-house)	Plastic ICs (Vendor Screen)	None	- 73.20	None	- 66.34
		+0.0078	-117.01	+0.0078	-106.44

Obviously this model is very detailed and requires a great deal of input data. Further, the selection of optimum configuration can swing widely with small changes in price and is therefore often valid for only a short period of time. For use as a tradeoff study in the conceptual phase of development, it would be simplified considerably to operate on estimates of part class types and budgetary cost estimates. The methodology, however, is applicable to the tradeoffs between parts selection and parts screening versus unit production costs.

Target Identification Set Detector

A study was conducted at Martin Marietta to evaluate the cost effectiveness of burn-in and combined temperature cycling with vibration screening. This assembly is composed of approximately 1500 circuit components mounted on printed circuit cards in a metal chassis. The chassis is mounted in a pod beneath the wing of an aircraft. The study consisted of tabulating the frequency distribution of failures and calculating the cost incurred for screening and testing. A summary of the details is given below.

A total of 42 target identification set detectors was deployed in the field for a total of 7,574 equipment days, varying from 85 to 252 days each. The average operating time was estimated at 0.22 hours per day per unit. Ten failures had been recorded, giving a point estimate MTBF of 167 hours.

During factory screening, 34 failures had been precipitated in these 42 units. The screening consisted of a 12-hour burn-in followed by 6 temperature cycles of 6 hours each at -65°F and $+130^{\circ}$F, combined with 2.2g, 22 Hz vibration. The cost of conducting this screening was estimated to increase unit production cost by 3.5 percent.

It is assumed that if no screening had been done, the 34 screening failures would have occurred in the field (probably within the first 180 days) and would have resulted in a field reliability MTBF of 38 hours instead of 167.

For this example a 3.5 percent increase in unit production cost produced a 340 percent increase in field reliability.

Tactical Missile

The tactical missile program experienced a serious reliability problem during initial production. An unacceptable rate of failure occurred in the guidance and control computer module. An examination of the test data revealed that one lot of 100 units had experienced 24 failures during an accumulation of 1600 operating hours. The point estimate MTBF calculated from this data was 67 hours.

A burn-in program consisting of 80 hours of operation with temperature cycling was designed by the computer vendor and implemented. A comparison of 130 units without burn-in and 290 units with burn-in was made as shown in the Table 7. The 130 units without burn-in exhibited approximately 100 percent reliability growth from the initial evaluation as a result of various other corrective actions which could not be explicitly identified. The burn-in produced an additional reliability improvement of approximately 137 percent for an increase in unit production cost of 5 percent.

TABLE 7. Computer Module Reliability Improvement

	Initial Evaluation	130 Units No burn-in	290 Units With burn-in
Operating time (hours)	1600	1900	3000
Failures	24	18	12
MTBF (hours)	67	106	250

Reliability improvement = $\frac{250}{106}$ = + 137 percent

Unit production cost increase = + 5 percent

Antiballistic Missile Parts Program

The antiballistic missile production program applied a very comprehensive part control and vendor surveillance system consisting of five individual steps - two by the component vendors and three in-house measures.

Certified Production Lines (CPL)

The four suppliers of the 26 components representing the highest usage and greatest demonstrated technical risk to the program were selected for this control. Essentially, their production lines were purchased outright to provide for absolute process stability, workmanship uniformity, and performance reliability. Supplier tools and test equipment were calibrated, and their personnel trained and certified to Martin Marietta standards. Methods, procedures, and processes were baselined, qualified, and frozen. Foremost, each line was placed under full-time Martin Marietta quality control to maintain product reliability disciplines.

Supplier Quality Source Control

The items controlled and monitored in this step (some 220 components produced by 45 suppliers) were high on the risk ladder; however, they did not warrant the time, effort, and expense involved in controlled production lines. Accordingly, supplier lines, tools, processes, and personnel were certified. Management and control, however, remained in supplier hands with Martin Marietta Quality engineers conducting continuous audits of critical process points, thus assuring no departure from qualified baselines.

100 Per Cent Receiving Inspection

New component reliability measures begin with 100 per cent inspection, test, and lead preparation. These provisions are the outcome of data gathered through exhaustive dissection analysis and corrective action initiated during the R&D program. Suppliers are advised whenever their products fail to produce desired receiving inspection results. This, in effect, places them on notice that failed parts will cost them. In response, supplier internal procedures today are tighter and component yields higher.

Dissection Analysis

All critical components are placed through worst case dissection analysis. This is to assure that suppliers make no changes to design, materials, processes, or internal component construction. No matter what the motive — economy, performance, design — all changes have impact on the component chain comprising system performance. Without notice and approval, no baseline changes are tolerated, no matter how well intentioned.

Storage and Aging

Addressing themselves to the effects of long-term storage on component performance, Quality personnel systematically draw samples from accepted lots, and put these through a series of periodic tests, evaluations, and comparisons to detect departure from allowable drift values.

The overall result was dramatic. By allocating funds to tasks designed to control and improve the reliability of component parts entering the production process, this program realized a 13 times improvement in the observed reliability of component parts with a concurrent cost reduction of $2.56 per part measured through the manufacturing/test cycle.

Inertial Navigation Sets I, II, III

This family of aircraft navigation and missile guidance equipment encountered reliability problems of a major magnitude. Several systems models, introduced into field service at approximately the same time, maintained a consistently high failure rate. The producer company initiated an in-depth review of all problem areas and, with top management backing, formulated an aggressive corrective program.

The central issue appeared to be the lack of rigorous, systematic testing with positive corrective action when failures occurred. An analysis of product defect origin showed that 30 percent of the problems were in-house, while 70 percent were vendor problems. After thorough study, the following reliability/quality improvement actions were taken:

1 A comprehensive reporting system was implemented, including detailed reporting of field failures. The INS contractor, the prime contractor, and the U. S. Air Force cooperated in this project. The feedback necessary to measure impact of changes was provided.

2 The INS contractor made a significant investment in facilities for automated testing and vastly increased the scope of testing to include:

Part Level

a 100 percent semiconductor testing at temperature extremes
b Continuity testing of multilayer laminates
c X-ray of printed circuit boards
d Leak test of all integrated circuits
e Solderability test of component leads.

Model and Assembly Level

a Automatic digital module testing
b 100 percent functional analog circuits testing
c All modules tested functionally at temperature
d All chassis/harness assemblies tested at temperature
e Computerized end-item functional test.

In addition, a number of design changes were made to increase performance margin. Good feedback data, receiving careful review by qualified persons, is the key to properly directing effective corrective action. After 18 months of evaluation, the results of this program are summarized as follows:

1 Improvement in parts, processing, and module level testing reduced system level test failures by a factor of four.

2 Overall costs in the system test cycle decreased by a factor of three.

3 Growth in field reliability grew by a factor of four.

Satellite Communications

Comprehensive testing of incoming material has been a keystone of this reliability program. The objective, formulated from experience from former programs, is to precipitate infant mortality or latent defect failures at the lowest possible level of assembly. At the lower level repair and rework can be accomplished quickly and at lower cost. Troubleshooting and failure analysis are more easily accomplished.

Reliability personnel work very closely with the purchasing agents to assure adequate evaluation of vendors. A close association with receiving inspection allows us to be on top of the problems at the earliest possible time. The old vendor adage, "Send it back, we'll give you a new one", just does not do the job. Quick analysis and positive corrective action are considered essential to maintain the levels of reliability needed in space programs. Generally, the sooner a reliability problem is recognized, the less it costs to solve it. Therefore, when evaluating cost tradeoffs for reliability, a judgment should be made as to how effectively and positively the failure feedback system works. This is measured by how quickly failure data is collected and reported and by how timely and conclusive the corrective action is.

Performance Monitor System

The reliability problems encountered on this program were complicated by areas of marginal system and hardware design. After a very poor percentage of data recovery was experienced in early operational tests, a design review board recommended numerous significant design changes, including improved tolerance in timing circuits, temperature compensation, and fail-safe logic in head and write circuits. Innovation in system redesign allowed dual function use of some circuits and provided a degree of redundancy. After these changes, and with the addition of burn-in screening, the operational reliability improved to a very satisfactory level for performance. The design improvements had very little impact on unit production cost.

This example serves to underscore the benefits of two reliability development techniques - the reliability design review and reliability growth testing. Had the discipline of these techniques been applied from the inception of this program, it is very likely that the overall schedule for operational deployment of a satisfactory system could have been measurably shortened and that total development costs would have been less. Further, the customer would have been spared the trauma of a false start with initial deployment and a period of doubt in the capability of the contractor.

The recurring labor, including repairs and failure analysis, required to perform the burn-in screening was estimated at 60 manhours per unit or approximately a 2 percent increase in unit production cost.

Multiplex set

This multiplex set is designed for operation in a ground fixed environment as defined in MIL-HDBK-217B. It is composed of approximately 8100 circuit components, which are mostly mounted upon copper clad glass epoxy printed circuit cards. The integrated circuits, approximately 1700, are purchased to the requirements of MIL-M-38510, class B. Most transistors and diodes are JANTX, and resistors and capacitors are established reliability at level P or higher. A reliability prediction of 4945 hours MTBF was made in accordance with the data and procedures of MIL-HDBK-217B. During the development program, reliability growth was realized by an extended demonstration of greater than 30,000 hours.

In production, upon completion of assembly and functional test, each unit is conditioned by a 48-hour burn-in at room ambient conditions followed by a 96-hour reliability test as defined as required in MIL-STD-781, test level A-1. All failures that occur during either burn-in or reliability testing are carefully analyzed and appropriate corrective action is taken. Summary reports of this activity are provided to the customer for his management visibility.

Cumulative production reliability test results through the first two quarters of 1978 indicate 11 failures during 34,094 hours. These results produce a calculated point estimate MTBF of 3100 hours, or at a single sided 60 percent confidence level, 2716 hours.

Automatic Test Equipment

This test system is mounted in a test bay, in 19-inch panel racks, for use in manufacturing test or depot maintenance to check out numerous assemblies and subassemblies. It operates in a ground fixed environment as defined in MIL-HDBK-217B, in accordance with which a reliability MTBF prediction was made. Two design configurations were considered. The first design employed all integrated circuits with screening to class C of MIL-STD-883, and produced an MTBF prediction of approximately 55 hours. The second design, which was ultimately adapted, was identical to the first except for one type of integrated circuit, type 8255. This integrated circuit, which accounted for 82 percent of the failure rate of the first design configuration, was screened to class B of MIL-STD-883 in the second configuration, resulting in a predicted MTBF of 223 hours.

After completion of assembly and test, the test systems were burned in for an average of 250 hours. The systems have been in field use for over 1 year and have recorded a point estimate MTBF of 275 hours or at a single-sided 60 percent confidence level, a mean time between failure of 218 hours, which compares favorably with the predicted MTBF. Class B screened type 8255 integrated circuits cost $38 each, while with class C screening the cost was $15 each, an increase of approximately 2.5 times.

Inertial Sensor Unit

This subassembly of a ground-to-air missile is comprised of several gyroscopes and accelerometers, which provide reference for the missile guidance computer. Early in the production phase, the failure rate of these components was averaging 22.5 percent for gyroscopes and 17.6 for accelerometers. The failure mode was parameter drift out of tolerance. A considerable effort in the category of vendor surveillance was necessary to produce corrective action for these problems. Ultimately, the sequence of final fabrication and test was changed and additional screening imposed on the vendor to reduce reject rates to less than 6 percent for both components. As a result, the unit cost of the components increased by $17 each. Since there are six of these components in each inertial sensor unit, the increase in material cost was $102. However, this produced a reduction of $126 in assembly labor due to fewer repairs, or a net saving of $24 per unit.

This program provides an example of how production labor is saved and unit production cost lowered by effective vendor surveillance. A secondary benefit is to substantially lower the risk of missing delivery schedules while discrepent material is returned to the vendor for repair or replacement.

Guided Projectile Limited Environmental Tests (LET)

This guided projectile is launched from a 155 mm howitzer in the same way as any conventional artillery round. Since it contains optical and electronic components for guidance that are subjected to very high shock levels, a unique test program is required to qualify and screen electronic assemblies during the final assembly acceptance process. Each unit is subjected to screening by three separate environmental stresses: thermal shock, mechanical shock, and random vibration. In general, the screening is applied at the first subassembly level below final assembly. It consists of six cycles of thermal shock, one mechanical shock along the major longitudinal axis, and 10 minutes of random vibration at 6g. This thermal shock screen differs from temperature cycling in that the transit time from high temperature extreme to low temperature extreme is very short. These screens require approximately 6 hours of setup time per projectile and 48 hours of labor to complete the tests. No reliability verification tests have been conducted, but analysis of the failure data collected from the screening tests indicates that reliability is enhanced by at least a factor of 7 as a result of the screening. Experimentation has shown that continuing thermal shock beyond six cycles does not result in any significant detection of additional infant mortality failures.

Missile Autopilot LET

Thirty-seven autopilots were screened by conducting mechanical shock and vibration tests. Two cycles of shock are performed at 165g with a sawtooth waveshape of 4 milliseconds duration. Four cycles of vibration are conducted at 5 to 10g with variable frequency between 50 and 2000 Hertz. Fifteen faults were detected and corrected, and no failures occurred in subsequent missile flight. The screening required 50 manhours to set up and conduct the tests.

3.0 MODEL DEVELOPMENT

A model that relates reliability achievement to the many program tradeoffs and their resultant cost consequences should delineate physical, measureable tasks or accomplishments and be subdivided along lines that are traditional for cost collection and reporting. The entire life cycle of the product should be represented.

3.1 Reliability Considerations

Below is a general expression for electronic equipment reliability that reflects three primary influences: development engineering, manufacturing, and field use and support.

$$R = MTBF_p (R_g) (R_m) (R_s + R_f + R_d)$$

where

R = mean time between failures at any given time

$MTBF_p$ = predicted mean time between failures in accordance with procedures in MIL-HDBK-217. This parameter implicitly accounts for the quality of purchased parts and the electrical and environmental stress and derating.

R_g = reliability growth. This factor generally varies between 0.1 and 1.0 and relates to the adequacy of the test-analyze-fix program during engineering development. A good program will result in a value of R_g equal to 0.9 or greater after about 10,000 hours.

R_m = manufacturing influence. This factor relates to the assurance that any manufacturing induced defects have been detected and removed.

$R_s + R_f + R_d$ = post deployment logistic support influence. R_s is a skill factor of operators and maintenance personnel. R_f relates to the adequacy of facilities, including work shops, special test equipment, and repair parts. R_d is a measure of the availability and quality of documentation, including operating and overhaul and maintenance manuals.

The basis for this reliability expression and the elements that influence it are shown pictorially in Figure 2. It is significant that product reliability is not a constant value but varies with the effects of these influences. The basis of this reliability expression will first be discussed in some detail and then related to impact upon unit production cost.

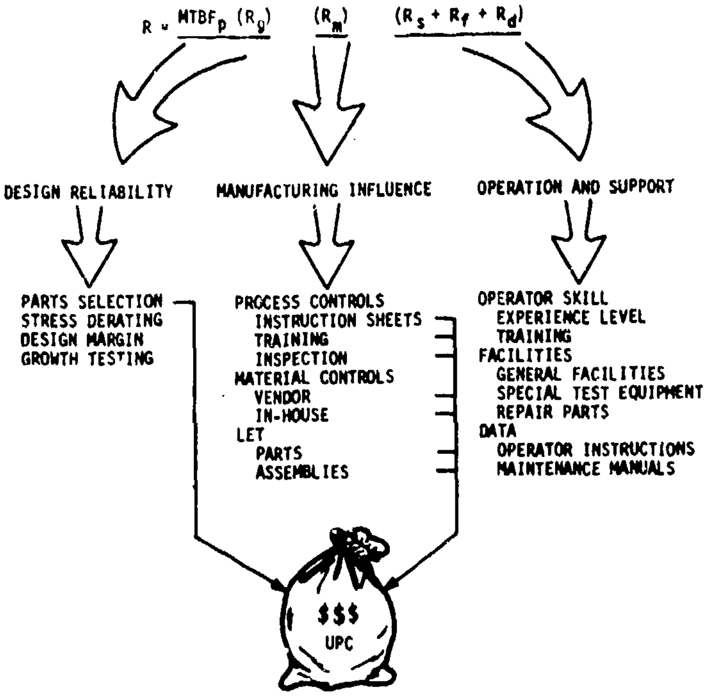

Figure 2. Breakdown of Reliability Equation for Cost Tradeoffs

3.1.1 Design Reliability Factor, $MTBF_p$ (R_g)

The prediction models as presented in MIL-HDBK-217 are developed from actual field failure rate experience and therefore are the logical reference for estimating the potential reliability of any given equipment. It has been shown in numerous studies that individual products can exhibit widely different results when compared to such a prediction, depending primarily upon the maturity of the design, the effectiveness of the manufacturing quality control, and upon operational influences.

General Electric (Reference 1) has shown that reliability demonstration of radically new designs will typically realize approximately 10 percent of the MIL-HDBK-217 prediction value initially, improving to near 100 percent according to a Duane (Reference 2) growth curve of variable slope determined by the effectiveness of reliability engineering during the design phase. Accordingly, the first two factors of the reliability equation, $MTBF_p$ and R_g, account for the influence of design and development engineering.

To predict the reliability ($MTBF_p$) of a given equipment configuration, the component parts are identified along with the design guidelines for environmental and electrical stress. The variables are:

1. The quality of parts chosen, such as established reliability (ER) level L,M,P,R,S, or T for passive devices; JAN, JANTX, or JANTXV for discrete semiconductors; and MIL-M-38510, class C, B, or A for integrated circuits. A typical example would contain a mixture of parts and, for conceptual design, may have to be grossly estimated as provided for in the procedure of Section 3 in MIL-HDBK-217.
2. The ratio of applied electrical stress to the device maximum rating.
3. The environmental exposure limits of temperature, vibration, etc.

With these variables specified, an $MTBF_p$ can be determined. To realize the potential of this prediction, a test-analyze-fix program is essential for debugging new designs. It generally requires repeated cycles of operation under all combinations of environmental stress, with positive corrective action to remove design defects.

R_g is related to the intensity and duration of the test-analyze-fix program according to the graph shown in Figure 3. When a well disciplined reliability program is followed with quick reaction to test problems, the slope of the curve can be expected to approximate the straight line, a = 0.5 as plotted on log log graph paper. The development of this relationship is covered in detail in the references perviously given (Reference 1 and 2). When combined into an integrated test program (not dedicated to reliability growth testing) or with less than top priority given to failure analysis and corrective action design, the growth rate can be expected to follow the slope of a = 0.25 or less. Evaluation of tradeoffs requires a judgement as to the appropriate value of a.

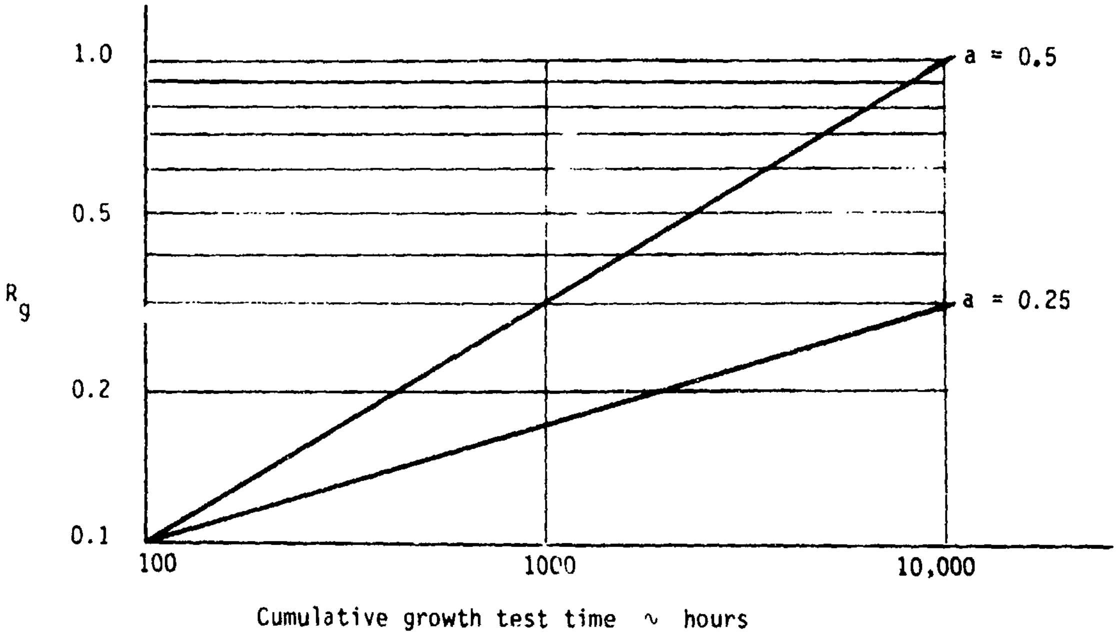

Figure 3. Reliability Growth Factor, R_g, versus Cumulative Growth Testing Hours

3.1.2 Manufacturing Influence Factor, R_m

In theory, it does not matter that numerous defects are introduced into electronic equipment during the manufacturing process, so long as they are detected and corrected prior to final delivery of the product. This position will be examined in much more detail in a later discussion of cost consequences, but for the moment it is submitted that for reliability achievement, it is sufficient to employ limited environmental testing (LET) to remove (or confirm the absence of) manufacturing defects (material and workmanship). The more rigorous this test, within design limits, and the more cycles of exposure, the greater the probability that all manufacturing defects will be removed.

Figure 4 is a graphical representation of the empirically derived equation for removal of infant mortality failures in electronic equipment by use of repeated variation of environmental stress:

$$R_m = 1 - (1 - E_c)^n$$

where

E_c is a measure of the severity of the test environments relative to the design limits

n is the number of cycles of environmental exposure.

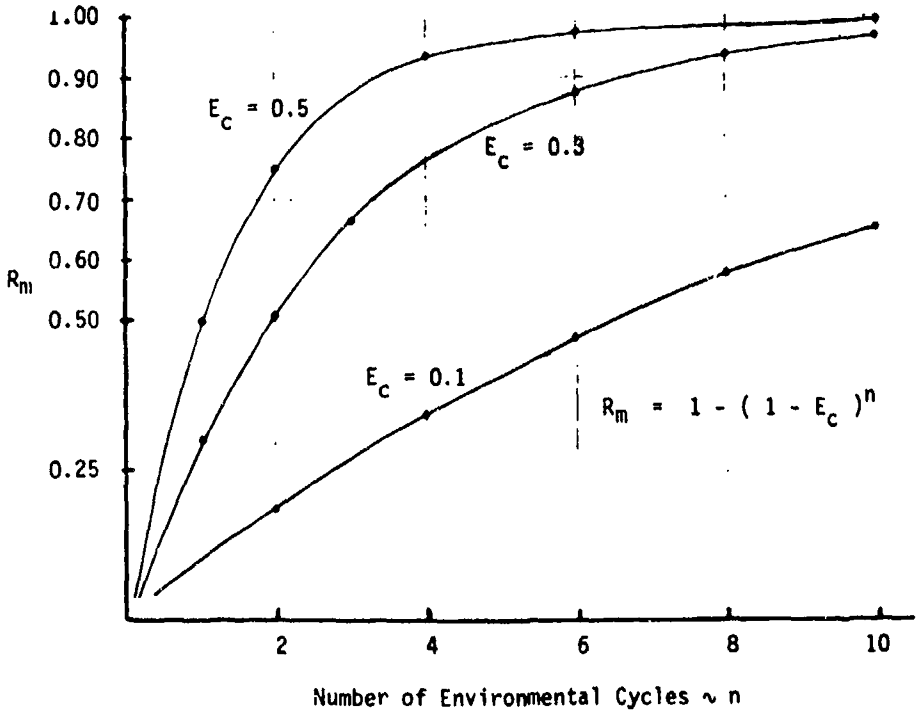

Figure 4. Limited Environmental Testing Impact

This expression is verified by data from an extensive study by R.W. Burrows (Reference 3) in which results of environmental screening practices of 26 electronic equipment manufacturers were summarized. The curves for three representative values of E_c are shown. One is for the case of combined exposure to the two most critical environmental elements, such as temperature cycling and random vibration, with levels equal to the design limits, $E_c = 0.5$. Another curve, $E_c = 0.3$, is representative of temperature excursions of 50°C and sinusoidal vibration at 2.2 g. The third curve shown, for $E_c = 0.1$, represents a burn-in screen where temperature is not cycled. To apply the equation, 8 hours of burn-in is equivalent to 1 cycle i.e., for a 48-hour burn-in, $n = 6$. For test profiles that do not approximate either of these cases, a value of E_c may be estimated by considering the relative severity of the intended test to those described above, keeping in mind that $E_c = 0.5$ is probably an upper limit for any practical application.

3.1.3 Operation and Support Factor, $R_s + R_f + R_d$

The final factor, $R_s + R_f + R_d$, is included in the model for completeness in accounting for total life cycle reliability. It has a negligible impact upon unit production cost and therefore will not be expanded upon further. For quantitative reliability predictions, this factor will approach unity as field training and familiarity with the equipment increases. A judgement can be made of the appropriate value for each analysis based upon comparison to current or recent experience with equipments of similar complexity and application in a given operational organization.

3.2 Cost Considerations

A general expression for the unit production cost of an electronic assembly is:

$$UPC = [M(1 + O_m) + L(1 + O_l)](1 + G\&A)(1 + fee)$$

where

UPC = unit production cost

M = direct material cost

O_m = material burden rate, if applicable

L = direct labor cost

O_l = labor burden rate

$G\&A$ = general and administrative burden rate

Fee = profit fee rate.

M and L are the variables that may be impacted by reliability considerations $MTBF_p$ and R_m as shown qualitatively in Figure 2.

3.2.1 $MTBF_p$ Cost Impact

To determine $MTBF_p$, it is necessary to specify the quantity and quality of component parts, including any requirement for supplemental screening testing. If complete material lists exist for all design configurations that are to be considered for tradeoff study, conventional cost estimating techniques are used to estimate the cost impact of each design. The model and methods previously described in the guided projectile design-to-cost study can be employed to select the best alternative with computer assistance if warranted.

For conceptual design, where detailed parts and materials lists do not exist for all design options, $MTBF_p$ is estimated by following the Section 3 method of MIL-HDBK-217, and the related material cost may be estimated from the relationships shown in Figure 5. Data was collected from several projects to compile Figure 5, which shows considerable variation and even some overlap in relative cost between the quality of part levels. Note that many different types of parts are represented and that judgement is required to select the most appropriate values.

In general, more exotic and complex parts will require a greater differential in price when quality requirements are increased. Conversely, common and simple parts can be tested extensively with relatively simple automation, resulting in very little increase in price. Set up charges, which must be prorated over each production lot, become quite significant when small quantities are involved. These factors were reflected in the data, and should be considered in using Figure 5 to estimate parts costs.

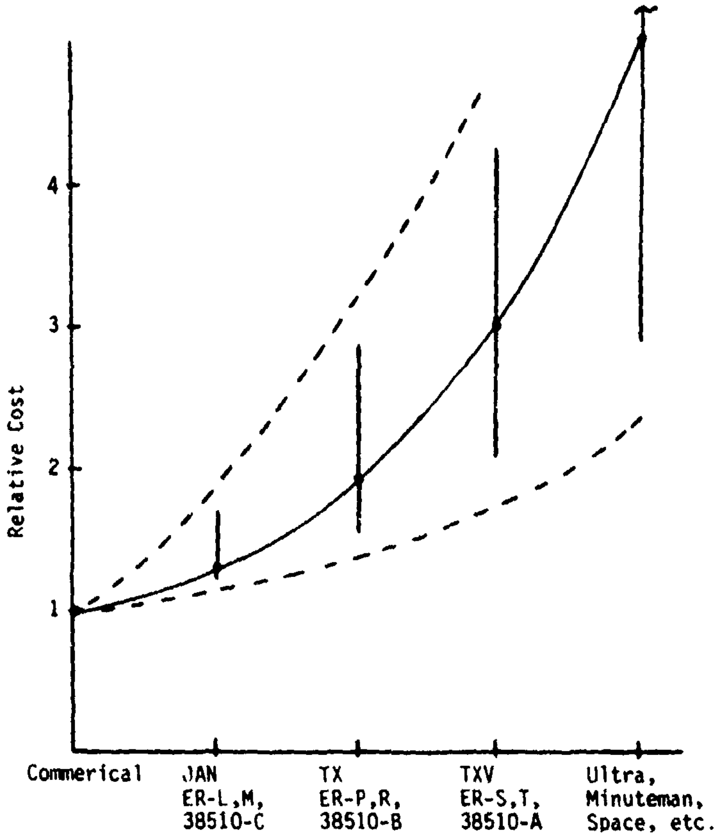

Figure 5. Cost of Purchased Parts versus Specified Quality

3.2.2 Manufacturing Cost Impact of Reliability

The cost impact of R_m (manufacturing influence upon reliability) is much more complex. Selection of a value of R_m for the reliability equation implies that a finished assembly, after completion of LET will have a corresponding freedom from manufacturing defects. There may have been many failures, subsequent repairs, retesting, or none. Only the end result is significant for reliability achievement.

However, the means of realizing the failure-free finished product may be very significant to the costs incurred. Generally, there are three philosphies for setting up the manufacturing operation:

1 Carefully control each step in the manufacturing process so that no defects are introduced. This is the preventive approach and incurs cost for careful analysis and planning of all manufacturing operations. If successful, few if any failures will occur during LET and little or no cost is incurred in troubleshooting, repair, and retest.

2 Somewhat the opposite of the above is to build up all assemblies with minimal control and plan on multiple repetitions of the LET to remove the numerous defects until subsequent test cycles demonstrate the unit to be failure free.

3 The other philosophy is to study the economics of the application of the first two approaches and choose to emphasize one or the other on an individual manufacturing operation basis.

Approach number 1 must be followed where the cost of a specific failure is extremely high, for instance, when human lives may be threatened. It is generally the preferred approach for very complex equipment that is in high volume production. Number 2 is most attractive for very low volume production or for relatively simple assemblies where troubleshooting and repair are very easily accomplished.

Most electronics manufacturing companies who deal with government contracts set up their manufacturing systems to facilitate both high volume and low volume production. Thus in most practical situations, approach number 3 is selected.

In general, manufacturing defects are avoided by careful adherence to detailed written instructions for each operation that have been thoroughly tested and proven to be effective. Such validated instructions apply to all manufacturing operations including procurement of material, in-house material handling, all fabrication and assembly tasks, inspection, test and package for shipment. Equal attention is required for housekeeping activities such as maintenance and calibration of test equipment, tools, gauges and measurement standards; personnel training and proficiency monitoring; and vendor selection, surveillance, rating, and control. To ensure that these instructions and controls are effective, a positive acting closed loop failure analysis and corrective action system is required.

For detailed analysis, direct labor, L, is subdivided into four categories:

$$L = L_{assy} + L_{test} + L_{sup} + L_{LET}$$

where

L_{assy} = all fabrication, assembly, and rework labor
L_{test} = all in-line test, inspection, and troubleshooting
L_{sup} = all quality assurance and production engineering including failure analysis and followup
L_{LET} = LET labor.

Emphasis upon preparation and maintenance of instruction sheets, along with failure analysis and corrective action generally requires an increase in support labor, L_{sup}, and results in less trouble shooting labor, L_{test}, and less rework labor, L_{assy}. This suggests a subset trade study to find the minimum labor cost to achieve the reliability level (freedom from manufacturing induced defects) implied by R_m. An example that illustrates these cost interactions is included in a later section (Pages 51-53).

One manufacturing control element that is very important to the efficient production of modern avionics equipment is the incoming inspection of electronic parts. When a defective part must be detected and replaced after assembly onto a printed wiring board, it is commonly estimated that the cost is 10 times that of detection at the incoming inspection point.

Further, if the printed wiring board containing a defective component part is installed into a higher assembly, the cost estimate for detection and repair increases to a factor between 30 and 100.

The cost impact of incoming inspection effectiveness is vividly illustrated by Table 8 from a recent study (Reference 4) on the detection of integrated circuit defects. Data was recorded for the distribution of detected failures per thousand ICs tested at various assembly levels and for three separate incoming inspection methods. One method was to inspect a sample of 30 percent of parts received; a second method was to conduct 100 percent functional tests, and the third was to combine 100 percent environmental screening in addition to 100 percent functional tests. Using the first method, 30 percent sample testing, 3.2 defects per thousand devices were detected at incoming at an average cost per defect of $0.50, 14.5 defects per thousand devices at the board level at a cost of $10 each, 3.2 defects at the system level at an average cost of $30 per defect, and 1.4 were detected in the field at a cost of $100 per defect. The detection cost per defect was proportionately higher for the other incoming inspection methods, $1 per defect for method two, and $6 each for method three, but the overall cost of removing integrated circuit defects from a system was $180 less for method two and $200 less for method three.

TABLE 8. Data Summary

Type of Incoming Inspection	Failures per 1000 Tested			
	Incoming	Board $ 10	System $ 30	Field $ 100
30 percent of devices tested	3.2 @ $0.50	14.5	3.2	1.4
100 percent of devices tested	15 $1.00	4.6	2.3	0.7
100 percent tested plus screening	21 @ $6.00	2.3	0.5	0.16

Figure 6 shows cumulative cost per system for the three methods. Another recent study (Reference 5) suggests that in the general case the cost per defect at the system level and in the field could be much higher, which makes the effectiveness of incoming inspection even more significant than this example indicates.

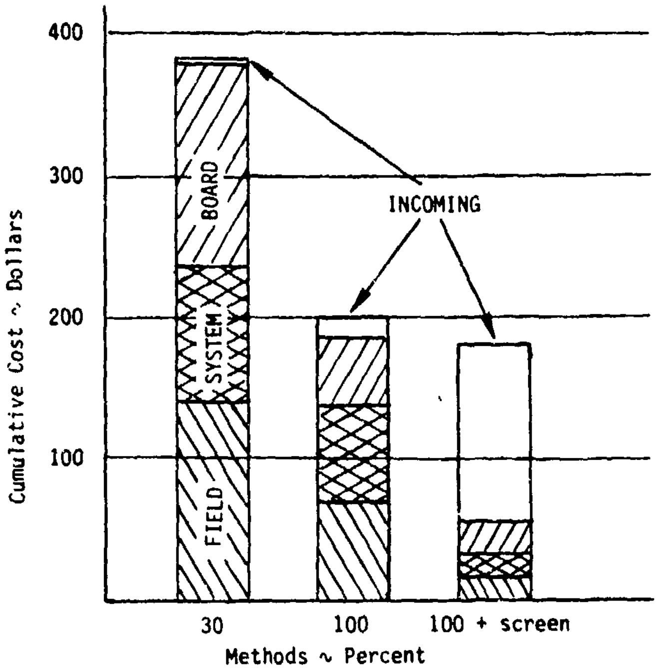

Figure 6. Cumulative Cost to Remove Integrated Circuit Defects versus Incoming Test Methods

The cost of conducting incoming inspection is frequently accumulated as a material handling overhead, designated as O_m in the UPC equation. For tradeoffs involving the degree of incoming inspection, this factor should be adjusted accordingly. The procedure is to estimate the differential cost of the inspection alternative and to add (or subtract) from the standard cost (usual or baseline method of inspection). For the previous example, the differential cost of adding 100 percent screening is $6 per defect times 21 defects, less $1 per defect times 15 defects for each 1000 devices tested. If the material cost, M, is assumed to be $2000 per 1000 devices, then an increase in material burden rate can be computed by dividing the added test expense by the material cost.

$$\Delta O_m = \frac{\text{new test cost - old test cost}}{\text{total material cost}}$$

$$= \frac{(6)\ (21) - (1)\ (15)}{M} = \frac{126 - 15}{2000} = 0.056 \text{ or } 5.6 \text{ percent.}$$

If the standard inspection method is to conduct 100 percent fuctional testing without screening, at a 15 percent total material handling burden rate, then a burden rate of 20.6 is used for any tradeoff alternative in which 100 percent screening at incoming inspection is chosen. Those companies who do not establish separate material burden rates may evaluate UPC tradeoffs by setting $O_m = \Delta O_m$, as calculated above, for any deviation from the standard incoming inspection method.

LET Cost

The cost of environmental testing (LET) takes the form of a fixed setup cost plus incremental costs dependent upon the duration of the test. From the reliability considerations, the value (or set of values) of R_m dictates the number of test cycles to be conducted. The LET cost therefore may be represented by the equation:

$$L_{LET} = L_{cyc}\ (n) + L_s$$

where

L_{LET} = cost of conducting a specific LET
L_{cyc} = cost of one cycle of LET exclusive of setup
n = number of test cycles corresponding to R_m
L_s = setup costs.

Graphical interpretation is provided in Figure 7. L_{cyc} and L_s are both directly proportional to the complexity of the unit under test, to the number of measurement points to be monitored, and to the length of time required to traverse one cycle, and inversely proportional to the amount of automation employed.

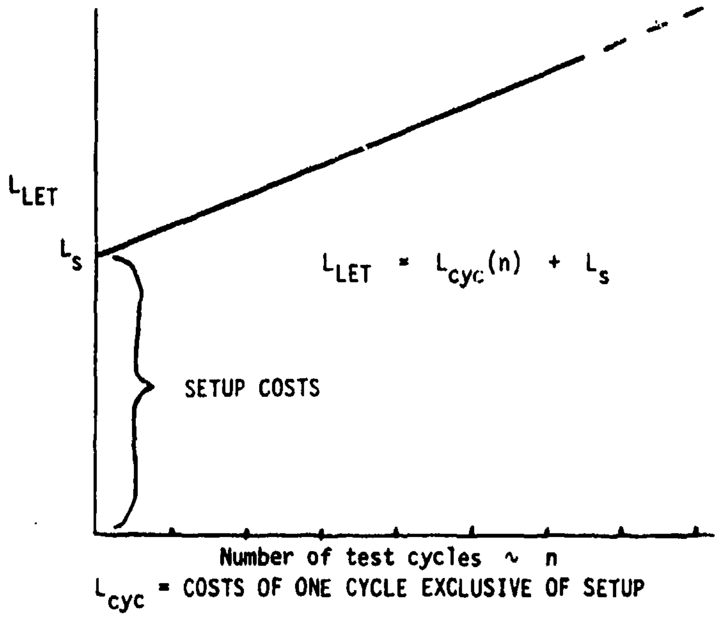

Figure 7. Limited Environmental Testing Cost Model

The cost estimating procedure is:

1 Given the specific test requirements, obtain an estimate of the setup costs.

2 Obtain an estimate of the cost of one test cycle.

3 Determine the number of cycles required by the value of the R_m.

4 Calculate L_{LET}.

3.2.3 Evaluating Tradeoffs

From the reliability equation,

$$R = MTBF_p (R_g) (R_m) (R_s + R_f + R_d)$$

it has been shown that variations in $MTBF_p$ and R_m alter unit production cost. From the UPC equation,

$$UPC = [M (1 + O_m) + L (1 + O_l)] (1 + G\&A (1 + fee)$$

M, O_m, and L vary with the reliability requirements. For evaluation of tradeoffs, a matrix is suggested of R versus UPC as follows. If there are i alternatives of $MTBF_p$ and j alternatives of R_m, a UPC_{ij} can be calculated for each R_{ij} according to the relationships developed. After calculating all combinations, the tradeoff evaluator has two alternatives; choose the least cost combination that produces an acceptable reliability, or choose the most reliability available at a given cost.

Example:

Given two choices each for $MTBF_p$ and R_m,

$MTBF_{p1}$ = 100 hours (use all JAN devices)

$MTBF_{p2}$ = 500 hours (all TX devices)

$R_{m1} = 0.975$ (six LET cycles, $E_c = 0.5$)

$R_{m2} = 0.75$ (two LET cycles, $E_c = 0.5$).

Since the factors R_g and $R_s + R_f + R_d$ do not significantly affect UPC, they may be removed from the analysis by assuming them equal to 1.

Then

$$R_{11} = 100\ (1)\ (0.975)\ (1) = 97.5$$

$$R_{12} = 100\ (1)\ (0.75)\ (1) = 75$$

$$R_{21} = 500\ (1)\ (0.975)\ (1) = 487.5$$

$$R_{22} = 500\ (1)\ (0.75)\ (1) = 375.$$

The cost associated with $MTBF_{p1}$ is M_1 = \$2500. From the relationships shown in Figure 4, the cost associated with $MTBF_{p2}$ may be estimated as M_2 = (1.5) (\$2500) = \$3750. A judgement has been made here that the cost of TX devices is approximately one and one-half times the cost of JAN devices for the mix of parts in this equipment.

For both R_{m1} and R_{m2}, the LET setup time is 4 hours at \$8, and cycle labor is 4 hours each at \$7. Therefore

$$L_{LET1} = \$28\ (6) + \$32 = \$200$$

$$L_{LET2} = \$28\ (2) + \$32 = \$88.$$

For R_{m1}, the following conditions are given:

Incoming inspection is 30 percent sample testing and the corresponding material burden rate is 11 percent.

L_{assy} is 60 hours at a direct labor rate of \$6.

L_{test} is 50 hours at a direct labor rate of \$8.

L_{sup} is 2 hours at a direct labor rate of \$10.

$$L_x = L_{assya} + L_{testa} + L_{supa} + L_{LET1}$$

$$= \$300 + \$400 + \$20 + \$200 = \$980$$

Therefore

$$UPC_{11} = [M_1 (1 + 0.11) + L_x (1 + O_1)] (1 + G\&A) (1 + fee).$$

Arbitrary values are assumed for O_1, G&A, and fee since they are constant for all tradeoffs.

$O_1 = 1.5$

$G\&A = 0.2$

$fee = 0.1.$

Then

$$UPC_{11} = [\$2500(1.11) + \$980(2.5)] (1.2)(1.1) = \$6897.$$

Substituting the cost of material associated with $MTBF_{p2}$,

$$UPC_{21} = [M_2 (1 + 0.11) + L_x (1 + O_1)] (1 + G\&A)(1 + fee)$$

$$= [\$3750(1.11) + \$980(2.5)] (1.2)(1.1) = \$8728.$$

For R_{m2}, two situations are considered, and hence two cost results for the same reliability result. The first situation is identical to R_{m1} except for the specified LET.

$$L_y = L_{assya} + L_{testa} + L_{supa} + L_{LET2}$$

$$= \$360 + \$400 + \$20 + \$88 = \$868$$

Therefore

$$UPC_{12a} = [M_1(1 + 0.11) + L_y(1 + 1.5)](1 + 0.2)(1 + 0.1)$$

$$= [\$2500(1.11) + \$868(2.5)](1.2)(1.1) = \$6527$$

$$UPC_{22a} = [M_2(1.11) + L_y(2.5)](1.2)(1.1)$$

$$= [\$3750(1.11) + \$868(2.5)]\ (1.2)(1.1) = \$8359.$$

The second situation for R_{m2} is with incoming inspection changed to 100 percent functional testing and a corresponding material burden rate of 13 percent. As a result, the breakdown of labor is

L_{assyb} = 40 hours at \$6

L_{testb} = 20 hours at \$8

L_{supb} = 10 hours at \$10.

The reduction in assembly and test labor is partially due to the more thorough incoming testing and partially due to increased quality support such as vendor surveillance and failure analysis.

The new labor total is given by

$$L_z = L_{assyb} + L_{testb} + L_{supb} + L_{LET2}$$

$$= \$240 + \$160 + \$100 + \$88 = \$588$$

and correspondingly

$$UPC_{12b} = [M_1(1.13) + L_z(2.5)]\ (1.2)(1.1)$$

$$= [\$2500(1.13) + \$588(2.5)](1.2)(1.1) = \$5669$$

$$UPC_{22b} = [M_2(1.13) + L_z(2.5)]\ (1.2)(1.1)$$

$$= [\$3750(1.13) + \$588(2.5)]\ (1.2)(1.1) = \$7534.$$

RANKED ORDER SUMMARY

R_{21} = 487.5 hours UPC_{21} = \$8728

R_{22a} = 375.0 hours UPC_{22a} = \$8359

R_{22b} = 375.0 hours UPC_{22b} = \$7534

R_{11} = 97.5 hours UPC_{11} = \$6897

R_{12a} = 75.0 hours UPC_{12a} = \$6527

R_{12b} = 75.0 hours UPC_{12b} = \$5669

The results shown here are of no particular significance, because the values selected for the variables may or may not be representative. The intention of this example is to illustrate the application of the relationships developed to the reliability versus unit production cost tradeoff analysis.

Tradeoff Model Test

As a test of the validity of the reliability model, the data from the multiplex set is used as an example exercise. The data given for this equipment included the reliability mean time between failure prediction, some details of the reliability growth development program, and the results and conditions of production reliability testing. As in the earlier example, the post deployment or logistics influence is normalized by setting the total of $R_s + R_f + R_d$ equal to unity. Recalling the reliability equation

$$R = MTBF_P (R_g) (R_m) (R_s + R_f + R_d),$$

first, substitute the predicted mean time between failure of the multiplex set

$$MTBF_P = 4945 \text{ hours}.$$

Second, estimate R_g. Since a very comprehensive growth program of greater than 10,000 hours has been conducted, it may be assumed

$$R_g = 1.$$

Third, estimate R_m. When a burn-in screen without temperature cycling is used, the stress that induces failure where manufacturing defects exist is much less, and faults will be detected at a lesser rate. One cycle of a typical temperature cycling screen will take 6 to 8 hours to complete. Therefore, in terms of exposure time only, 48 hours of burn-in equates to approximately 6 to 8 cycles. Choosing $E_c = 0.1$ and $n = 6$, solve for R_m

$$R_m = 1 - (1 - E_c)^n = 1 - (1 - 0.1)^6 = 0.47$$

The resulting predicted reliability is then

$$R_1 = 4945\ (1)\ (0.47)\ (1) = 2324 \text{ hours.}$$

This compares favorably with the observed failure rate, calculated at the 60 percent confidence level, of 2716 hours.

A tradeoff was considered where less expensive, lower quality parts would be substituted and more rigorous screening conducted on the completed assemblies. For this second configuration, all integrated circuits would be specified to requirements of MIL-M-38510, class C, and descrete semiconductors to JAN. The resulting reliability prediction in accordance with MIL-HDBK-217B was 2060 hours. The new screening requirement for completed assemblies included 6 cycles of temperature cycling from 0 to 50 degrees centigrade combined with 2.2g vibration at 60 Hertz. It was assumed that these variations would have no effect upon the results achieved by reliability development growth testing. The alternate reliability was

$$R_m = 1 - (1 - E_c)^n = 1 - (1 - .3)^6 = .88$$

$$R_2 = 2060\ (1)\ (0.88)\ (1) = 1813 \text{ hours.}$$

The actual cost of the multiplex equipment gives a UPC_1 corresponding to R_1. Recent average production values are

Material, M_1 = \$7400
Labor, L_1 = \$3160
O_m = 0 (redistributed into labor burden)
O_1 = 150 percent
G&A = 20 percent
Fee = 10 percent

$$\begin{aligned} UPC_1 &= [M_1(1 + O_m) + L_1(1 + O_l)](1 + G\&A)(1 + fee) \\ &= [\$7400 + \$3160\ (2.5)](1.2)(1.1) = \$20{,}196. \end{aligned}$$

The alternate cost, UPC_2 corresponding with R_2 is

$M_2 = \$5300$

$L_2 = \$3760$ (increased because of added setup time for screening and more test and repair due to lower quality parts, i.e., more defects detected)

$UPC_2 = [\$5300 + \$3760(2.5)](1.2)(1.1) = \$19{,}404.$

Summary Data

	Reliability	Cost
Alternate 1	2324 hours	$20,196
Alternate 2	1812 hours	$19,404

Alternate 2 was not selected because although it results in a 4 percent cost reduction, the reliability is reduced by about 22 percent to a value that did not meet the requirement.

This example demonstrates the utility of the estimating relationships as well as showing excellent correlaton between predictions and actual results observed.

4.0 STUDY RESULTS

An objective of this study has been to find a method for guiding engineering tradeoff decisions during the conceptual phase of design or to assist the procurement officer in evaluating the reliability plans of alternate proposals. The ultimate achievement of this goal would reduce these decisions to the application of simple equations where coefficients and variables are discrete, consistent, and clearly defined. When the variable is cost, however, this thought is somewhat sophomoric at best.

Any quotation by a vendor of parts, for example, is subject to the bargaining skills of both buyer and salesman, to current sales volume of those parts, to backlog of orders in the vendor's plant, to the vendor's marketing emphasis at the time, to other related sales orders between the two parties, and many more current circumstances. These factors cannot be ignored. To account for them in making engineering tradeoff decisions requires great intuition and judgment.

Since it is beyond the scope of this study to deal with these matters, it will suffice to caution the reader that a great deal of judgment will continue to be required in making cost tradeoffs. The results of this study are presented in a manner which attempts to retain perspective of these judgmental factors. Sophisticated mathematical manipulation of the data has been foregone. The population of data elements, from a statistical analysis point of view, is quite small and dependent on so many independent variables that a mathematical approach is quite likely only to obscure the process of customizing these results for use in tradeoffs under different conditions in different companies.

This analysis consists of the logical arrangement of observations gathered from product histories and the subsequent interpretation of significance of these histories to the general question of reliability versus unit production cost tradeoffs. Through the thorough understanding of the role of each of the reliability elements to a specific new program, the engineer will then be able to judge the proper weighing factor to apply to each element.

One point must be emphasized. The engineer is developing or evaluating a total program, and results will reflect that total program. So while we concentrate on incremental relationships of individual reliability program elements to the dependent variables, reliability, and unit production costs, the dependencies to other program elements must be kept in mind. Each company will have inherent emphasis of reliability elements embedded in its operation based upon prior programs. The cost to emphasize a specific reliability program element for the next program will be different than for some other company. Selecting the optimum reliability program then requires not only an understanding of the role of the various reliability elements, but also a careful examination of recent performance (reliability track record) of the company.

Correspondence and interviews with reliability spokesmen for the companies contacted during the study were unanimous in underscoring two major areas that determine whether field reliability achieves its inherent potential. First, there must be adequate development of reliability growth prior to production; and secondly, there must be rigorous controls on materials and processes during production. The reliability elements studied here contribute almost entirely to the second category and assume prior accomplishment of growth.

A high degree of parts standardization vastly reduces the cost of maintaining control on materials and processes. It should command a prominent position in any development work statement. Parts standardization requires a considerable effort, usually considered as nonrecurring, to keep abreast of new vendors, products, technologies, and processes which continually change the relative reliabilities of parts applications. In a given company, parts standardization requirements usually are consistent for all programs; and, therefore, a portion of this effort is sometimes considered an overhead expense.

If there are no specific costs (engineering labor) in a cost proposal for a parts standardization effort during a development program, the manner in which the above considerations are accounted for and controlled should be carefully investigated. Previous studies, reported in the literature (References 6 and 7), suggest that when including effort for vendor control, these costs should constitute approximately one-half of the reliability program nonrecurring cost total. Shortcuts here will make material control during production much more difficult. Case histories reported here show that when this discipline is neglected, an unreliable product results. When corrective action is taken to implement parts control, unit production costs inevitably decrease because of reduced test time, reduced scrap and rework, and overall improved material handling efficiency. The proportionality constant for this relationship will vary widely. Careful investigation of each contractor's cost estimating relationships, assuming that they are adequately founded, is the best way to evaluate these tradeoffs.

Vendor surveillance is closely related and often integrated into the parts standardization and control program. It is necessary to assure that proper attention is given to failure analysis and corrective action resulting from incidents involving the vendor's product, either in the manufacturing process or subsequently, and is essential to efficient material control. The same company by company evaluation as described above for parts standardization is required to determine how much vendor surveillance is cost effective. Starting up a vendor surveillance program where none had previously existed is significantly more expensive than maintaining an ongoing effort. Again, review of performance on past programs provides a yardstick for tradeoffs when considering the unit production cost impact of vendor surveillance.

Screening and testing programs can be evaluated with considerably more objectivity than most other reliability program elements. Test routines can be clearly defined and labor and facility costs can be readily estimated. It is in this area then that directly relating costs and expected reliability tradeoffs can be mathematically calculated with meaningful results. In an earlier section of this report, an example of such a trade study was given for the case where a complete bill of material is known along with exact quantities to be used. During a proposal or in the conceptual design phase, this level of detail is probably lacking and fewer firm prices are known. However, without great sacrifice in accuracy, these parameters can be estimated and valid comparisons can be made. With the aid of rather simple computer programs, many iterations of large parts population assemblies can be tabulated, summed, and compared.

The impact of the various reliability elements upon ultimate equipment reliability and upon unit production cost can be predicted when one understands the relationships. Mathematical models have been established for this purpose after study of the data collected and the literature. The analysis process is to first collect the reliability element factors in order to estimate the total reliability. Then collect the cost consequences of each reliability element to determine the total unit cost. Each tradeoff will produce a pair of values of reliability versus cost from which an optimum can be chosen after all variations of interest have been computed.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Reliability versus unit production cost relationships vary widely from situation to situation. Valid decisions on these tradeoffs are possible using a combination of judgmentive and objective evaluations of the specific situation. Several situations have been reviewed to provide understanding of representative results of individual reliability program element applications.

There are basically two cost elements involved in any cost trade study - material and labor. Methods for evaluating material cost tradeoffs are described. Labor tradeoffs should be evaluated with consideration to results achieved in controlling materials and processes during production. These require a review of history and cost estimating relationships for the specific company.

A design engineer, evaluating tradeoffs in the conceptual phase should determine if the reliability objective of the new equipment is consistent with results currently being achieved with designs of comparable complexity. If this criterion is not met, a business as usual development program probably will not achieve the objective. A review of a company's track record on selecting good vendors, having an adequate design review, implementing effective test programs, and timely problem solving should be made. If a weak spot is found and reliability objectives require improved company performance, a program should be drawn up and made a part of the new proposal. If company performance has been satisfactory to achieve or exceed the reliability objective, the cost estimating group will have the necessary information to provide cost estimating relationships for use in the tradeoff decisions.

A prospective buyer, seeking to evaluate alternate reliability program proposals, should also attempt to measure the current achievements of each prospective vendor. If there is a conflict between requirement and past performance, the proposal should address the problems and offer feasible solutions. Through an understanding of the roles of the various reliability program elements and by applying the specific cost estimating relationships on a company by company basis, the preferred program can be selected.

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APPENDIX

Companies Contributing to Study

Martin Marietta Corporation
Orlando Division
Orlando, Florida

Litton, Guidance and Control Systems
Woodland Hills, California

Rockwell International
Autonetics Division
Anaheim, California

Rockwell International
Collins Radio Group
Newport Beach, California

Northrup Corporation
Aircraft Group
Hawthorne, California

Interstate Electronics Corporation
Anaheim, California

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