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FINAL REPORT

FEASIBILITY OF DEVELOPING LSI MICROCIRCUIT RELIABILITY PREDICTION MODELS

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Prepared for

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ABSTRACT

The results of this feasibility study are summarized here in abstracted conclusions. The basis for, and proof of the validity of these conclusions are developed in the body of the report.

1. Based on prediction success with an interim approximate model for LSI prediction as contained in the Hughes R-67-3 "Designers Reliability Handbook", and with preliminary examples herein of a new basic prediction method it is considered feasible to develop more accurate LSI prediction models of the new advanced type.
2. These conclusions are based on a detailed study of part and present prediction modeling efforts and potential improvements described herein that can logically follow the advanced modeling achievements also described. Guidelines and tools for the generation and validation of practical more accurate prediction models have been developed. These include:

   - An understanding of the original state of defects in raw materials and their meaning for reliability.
   - The impact of manufacturing processes and workmanship errors on the content of defects of various types that control failure mode distributions and failure rates.
   - Improved ability to specify and perform tests and screens to remove defects and prevent failures.
   - The interaction effects of applied stresses with time that determine demonstrated reliability during any stress interval.

- The definition of failure mode and mechanism families and the relation of these to microcircuit life cycle history.
- The definition of other key factors and their interrelationships that are explained by several series of supporting models.
- A body of new modeling theory that enables the construction of practical engineering-type mathematical models.
- The analysis and understanding of reliability cause and effect as these relate to the design and manufacture of reliable LSI microcircuits.

3. Past failures in the field of prediction were analyzed. Errors in past philosophy and approach were discovered, and not only were the methods of modeling most likely to be successful identified but pitfalls to be avoided were revealed.
4. This study included analysis of large scale hybrid arrays and fully integrated monolithic LSI microcircuits. It is believed that the proposed new models can apply effectively to both types of LSI and also to the new Extra Large Scale Integrated (ELSI) microcircuits.
5. Preliminary or interim type LSI prediction models have been used successfully for several years by the Hughes Aircraft Company on large system programs. This experience provides data and direction for the next effort of developing the proposed more accurate basic type prediction models. The presently used LSI prediction technique is explained herein. In appendix B are procedural sheets for making hybrid LSI predictions that are photographically reproduced from the Hughes Designers Reliability Handbook R-67-3. Similar excerpts could have been shown for totally monolithic LSI microcircuits. In general these are simpler techniques that can take advantage of the greater standardization that has been achieved in monolithic LSI's
6. It is believed that the feasibility of the proposed new models is demonstrated by the surprising accuracy of prediction demonstrated on the F-14-XN3 system. The conventional handbook approach

such as the interim model method in appendix B can only predict the height of the bottom of the "Reliability Bathtub" failure rate curve. This prediction was λ_{BB} = 0.28% per thousand hours for the several hundred hybrid LSI microcircuits involved. Actual flight and field service data indicates a decreasing failure rate with time that has slightly surpassed this predicted value at the end of 4,600 hours. During the first 1,600 hours of operating life the average failure rate was λ_{1600} = 2.0% per thousand hours. During the following 3,000 hours the average failure rate was λ_{3000} = 0.24% per thousand hours. The feasibility of the proposed more accurate basic models is demonstrated by the application example using many preliminary and assumed parameter values. The new basic models have the advantage that they can predict failure rates at any time interval even before the bottom of the "Bathtub" has been reached. With these models there is no need to assume that a constant failure rate exists. Even with the approximate parameters used, the new basic model approach predicted a λ_1 = 0.36% per thousand hours for the first thousand hours of life and λ_2 = 0.10% per thousand hours for the second thousand hours of life. Many approximations and preliminary hypotheses used herein to demonstrate the practical feasibility of the proposed new models, should be refined and perfected in the next stage of development.

7. Reasons for failure of past prediction efforts have been explained in a study of seven schools of thought on hybrid reliability prediction. Errors in approach, technique, or interpretation of results from these seven schools have been analyzed, and their better features have been harmonized with actual data in a proposed improved prediction approach. Each of the seven schools of thought contains good facets of approach, theory and data that have been assessed, interpreted, and adapted for use in developing improved models. The distorted concepts and technical bias in these schools of thought have also been identified and categorized for future avoidance in modeling efforts.

8. In the process of studying the feasibility of developing practical hybrid reliability prediction models, two other aspects of feasibility became apparent. These two related "needs" require development for NASA use of the type demonstrated in the successful use of the Hughes Interim Hybrid prediction technique. The other two needs are described below:

   a. Methods and procedures for making the most effective use of the new prediction models. (On programs of various types with different urgencies, complexity, time and cost constraints key reliability problems and application stress conditions -- these programs are in different stages of development and reliability achievement at the times that the models are applied.)

   b. Guidelines and pedagogical material with which to implement training and indoctrination for the most successful use of the new models, techniques, methods, and procedures. (For training under various conditions and program exigencies, of people with different technical orientation, in various levels of organizational authority, responsibility and industrial discipline such as line management, service functions, quality control, reliability engineering, product design, production planning, and Government assurance, etc.)

9. Even a casual study of the literature reveals many discrepancies and apparent contradictions in published failure data and failure mode distributions for LSI microcircuits. These discrepant data can be explained and made use of in developing and applying practical reliability prediction models. Even the prediction approaches which have failed can be interpreted for valuable lessons learned that will be helpful in the proposed next stage of modeling effort. Most available failure mode data, for example, are meaningless for future prediction unless the detailed results (not the conclusions) are interpreted according to newly established laws of failure, principles of screening, methods of prediction, and concepts of

time-stress-detection interdependency. These technical tools are now developed for immediate application.

10. Failure mode distributions (Pie Charts) that appear in the literature as computed from data applying at some time or stage of system manufacture and use, have been found to relate to many cumulative factors of the past that are not usually presented with the pie charts. These missing background facts include the maturity of the design, the factory and process controls that were used, the nature of the system and its complexity, the amount of screening that has preceded the applicable milestone at which the distribution is computed, and the total past stress history in manufacture, test and use. All these factors are defined, they can now be measured in practical terms, and they are interrelated in one or more of the eight series of basic math models recently developed at Hughes Aircraft Company by these same authors. These new models provide a basis for understanding the interaction effects of stresses with time and man-machine interfaces with the process and final product characteristics. In general the present model coverage is of defect generation, detection, and control in preparation for delivering known reliable systems at the optimum lowest cost. These models are a natural springboard from which to develop the proposed new basic models for hybrid reliability prediction. It has been found that most of the information needed in any given case for this kind of prediction is already measured and recorded in existing program records lacking only guidance in its extraction and summary in specific form for its immediate understanding and use.

11. Accurate failure rate predictions and quantities of failures to be expected during specific subsequent stress intervals can be computed from known and presently recorded failure mode and time-stress conditions. Demonstration tests, storage and logistic support intervals, or special mission use periods are the future time-stress intervals for which predictions can be made. The

models to be developed represent simplified technical tools that are validated extensions of present useable techniques and models.

12. By the proposed modeling approach, when any of the essential key factors are not known initially, they can be approximated in various ways with a known impact on the accuracy of the final predictions. For example, on any program where reliability predictions are started at interim states of project completion, a-priori approximate estimates of the key factors can be established for making preliminary predictions. Later these can be refined for greater accuracy as subsequent program information of a more definitive nature becomes available. Specific steps to develop, validate and verify these new models are described in the recommendations section V.

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I. INTRODUCTION

The objective of this program was to determine the feasibility of developing practical reliability prediction models that can be used to estimate the reliability of space systems utilizing Large Scale Integration (LSI) microcircuits. The conclusion reached is that it is feasible to generate and use such models successfully. This conclusion is based on a study of past and present prediction modeling efforts and potential improvements that can logically follow the present advanced developments in this field.

Not all of the conclusions reached in this study can be substantiated with equal rigor. Those relating to successfully accomplished prediction efforts can be validated by reference to the achieved facts. This is only possible in the past tense and for the limited use of large scale hybrid arrays that can be cited for the past.

Conclusions based on efforts in the past that were not successful in achieving their intended objectives are not so easily substantiated, but these are non-the-less real and valid. Past failures can be interpreted if reasons for failure are known as well as the results that would have occurred if certain changes in approach or technique had been applied. This knowledge is always acquired after the unsuccessful events and thus is never included with the failure record. Frequently the most valuable lessons learned from any past incident can never be learned directly from the immediate recorded history. Adjacent history and subsequent interpretations of results must be assessed before the real achievements of each failure become apparent. For example, the final construction of the first successful electric incondescent lamp depended on the interpretation of the reasons for failure of all the previous unsuccessful attempts. Without the previous failures the final success would not have been possible.

The feasibility of hybrid LSI reliability prediction has similar qualifications. Some success with preliminary hybrid prediction models can be cited. But most of the prediction and modeling success in the past has not been directly related to hybrid LSI prediction. Most of the LSI approaches in the literature representing some seven schools of thought in reliability have either been tried by someone with only partial success, or would have been proven unsuccessful had they been tried, largely because of inherent weaknesses in the approach or proposed methods of application. A major weakness of most techniques and mathematical models for prediction is their complexity which makes them too cumbersome for practical application.

Thus, although not enough proof data to be considered statistically valid can be submitted proving that highly accurate hybrid LSI prediction models are feasible, there is much evidence that they will be feasible when they are properly developed and applied using recently proven principles and techniques. Emphasis here is on both the principles of development and the principles of of successful application after they are developed and validated. As with any sharp tool the inexperienced user can injure himself, damage the individual tool, and by ineffective use give the whole class of similar tools a bad name. This is the source of some negative feeling in the past about reliability prediction in general, and points up the need for advanced training and indoctrinal efforts for the successful application of the new prediction models after they become developed. This threefold set of feasibility factors can be illustrated as in Table I.

Based on specific results from this feasibility study and previous achievements in similar modeling efforts by the authors of this report, the achievement of success with all three feasibility factors of Table I is adjudged feasible. It is fortunate to be able to report that preliminary type hybrid LSI prediction models have been used successfully at Hughes for the past several years. Not only were the models developed but official approval for their use on major programs was established; people were indoctrinated in their specific application, and results from their successful use are available for the next step of developing more accurate models. In addition numerous conclusions can be cited from this feasibility study that supplement and augment the confidence of this analysis team

TABLE I. MAJOR FEASIBILITY FACTORS

A. Develop and Verify More Accurate Hybrid LSI Prediction Models and Techniques based on past and present evidence.

B. Develop Methods and Detailed Procedures:

- For making the most effective use of the new prediction models
- On programs of various types with different complexity, inherent reliability, time and cost constraints, program objectives, and demonstration or application stress conditions
- For programs that are in different stages of development and reliability achievement at the times that the models are to be applied

C. Establish Guidelines and Training Material:

- To implement worker and management training and inductrination programs
- For the most successful and cost effective application of the models, techniques, methods and procedures
- Under various conditions and program exigencies
- By people with different technical orientation and perspective
- In various levels of organizational authority and industrial discipline such as line management, quality control, reliability engineering, product design, production planning, Government Assurance, etc.

that successful achievement of more accurate prediction models for use with large scale hybrid arrays is but a short step away.

Although this project was originally aimed at large scale hybrid LSI microcircuits, the question can be raised of applicability of the models to fully monolithic LSI's. This question is important because of the current trend toward use of an increasingly greater proportion of monolithic elements in hybrid arrays. This trend probably will continue so that future extra large scale microcircuits (ELSI) are likely to consist largely of interconnected monolithic LSI chips. No special challenge will be posed to the feasibility of valid prediction models as described in this report. It represents merely a change of emphasis in computation from the hybrid functions to the monolithic functions all of which will be included in the proposed LSI models.

All types of problems inherent in monolithic IC's are common to large scale hybrid arrays. This feasibility study has included a thorough literature search for concepts, approaches, methods of prediction, and specific data concerning failures of both hybrid and monolithic integrated circuits. This report summarizes results from this study and describes guidelines for understanding and interpreting past prediction results as they relate to Hybrid and Monolithic LSI in providing for such factors as IC design, system application, use requirements, manufacturing, process and quality control, testing, screening, reliability demonstration, final field use, and total cost effectiveness. All these factors must be considered for successful prediction and can be given feasible coverage in the next generation of LSI prediction models.

II. SCHOOLS OF THOUGHT IN PREDICTION

This feasibility study has revealed the philosophy and approach inherent in seven different schools of thought on LSI reliability prediction. Each school has merit from a given limited perspective which, when understood, explains many otherwise perplexing anomalies and apparent mysteries. A knowledge of the basic approaches taken by each school is necessary for understanding much of the data and technical arguments in the literature that commonly seem contradictory or irrelevant. In addition many contributions from all seven schools can be used in developing the most successful final prediction approach.

Each of the seven schools of thought has been analyzed for its reasons in being, the validity of assumptions made, and for bias or error that might have entered into each specific interpretation of data. In the following discussion a few practitioners are cited in each school so that reference to their published papers can explain the school. The lists are neither all-inclusive or exclusive and contain the names of only a few outstanding practitioners of each philosophical approach. Many others could be listed for each school in a more complete history. In addition it should be emphasized that some practitioners are personal believers and sometimes professionally active in more than one school. It is believed that each philosophy and its resultant technical approach can make an understandable contribution when it is properly integrated into the whole philosophical picture of LSI prediction.

In simplified perspective the seven significantly different schools of thought on LSI reliability prediction can be characterized by the following titles:

1. Gross Statistics School
2. Failure Rate per Function School

3. Purest Reliability Physics School
4. Failure Mode Confidence School
5. False Categorization School
6. Complexity Independence School
7. Failure Rate per Identifiable Physical Unit School

Most of these schools lead to impractical LSI prediction methods because they fail to recognize that LSI's are essentially complex systems in miniature. Without this recognition the essential differences between systems which result from their complexity, multiple functional capability, and intrasystem interactions lose definition. With this loss, the impact of these factors on reliability cannot be estimated.

Sometimes because the individual practitioners recognize the need for integrating several schools of thought, but more often because of loose thinking, the total philosophic approach is made more difficult by the widely individualistic characteristics of the operators in each school. The same arguments are sometimes used by different individuals as justification for completely contradictory actions and interpretations of results.

One common operating characteristic of many individuals is to focus on a small piece of knowledge and run with it as a sole guide until impact is made with a firm barrier. At this point the most common tendency is to drop that particular piece of knowledge and start running in another direction with another piece. Repeated similar futile exercises have resulted in such derogatory epitaphs as "Numbers Racket", etc. No attempt is made herein to deal with all these foibles and inefficiencies. Rather an understanding of the basic schools of thought is attempted for interpreting their experience.

The hungry man considers all things beneficial which move him closer to his intended dinner. If in the process of moving closer his actions may block someone else from moving in, this is understandable in the framework of group activity. A minor block from an individual standpoint does not alter the average trend for everyone to eat during certain lunch hours. The subject of LSI reliability prediction has characteristics similar to this cafeteria example. Various paths to essentially the same end are frequently blocked temporarily by a combination of circumstances or approach. Unfortunately in many reliability cases a minor temporary block has been misinterpreted to be a permanently closed path, and the interrupted one turns around and goes out hungry. Lack of overall perspective has caused many prediction results to appear as anomalies when in truth they have been but a short step from major progress. Many basic objectives and techniques of the seven schools of thought in prediction are not greatly different and can be coordinated for mutual advantage. Better understanding and improved application of methods can result from a study of the seven basic schools of thought. When the strengths and weaknesses of these various schools of thought and approach are understood and appreciated, the feasibility of developing successful hybrid reliability prediction models becomes obvious. The seven unique schools of thought are described in the remainder of this section.

A. GROSS STATISTICS SCHOOL

The gross statistics school uses the approach that ignores design details and random defects, puts major emphasis on failures resulting from gross quality defects caused by process error, and does not recognize the key role or impact of reliability screening. Perhaps the major proponent of this school of thought is the RADC-RAC-IIT (Reliability Analysis Center sponsored by RADC at Illinois Institute of Technology).[1]

B. FAILURE RATE PER FUNCTION SCHOOL

The failure rate per function school emphasizes failure rate per function accomplished, rather than failure rate per chip or per package and concentrates on failure statistics and detailed analysis of failure mechanisms without direct application of the mechanism models to practical reliability prediction models. Two key proponents in this school are G. L. Schnable[2] and R. S. Keen of Philco-Ford.

C. PUREST RELIABILITY PHYSICS SCHOOL

The purest reliability physics school is concerned with studies in depth on causes of failure and failure mechanisms with emphasis on effective corrective and preventive action. This school concentrates on techniques of analysis and related instrumentation with little regard for practical applications in prediction. The concept of this school seems to be, "Understand the cause and prevent the reoccurance. Once a solution is found the basic problem is no longer considered a factor in prediction." Chief proponents in this school include James Black[3] and Elliot Philofsky[4] of Motorola and G. V. Browning[5] of McDonnell Douglas Astronautics.

D. FAILURE MODE CONFIDENCE SCHOOL

The failure mode confidence school has proposed that direct correlation can be established between failure modes, manufacturer's variable factor, and human variability in operation and use. This basic concept is to obtain statistical confidence on the contribution to failure of each likely failure mode as a function of time. Presumably by determining the rate of propagation of a degradation mechanism in one device design, the findings can be extended to another design employing the same or similar materials, geometries, and manufacturing processes. This idea is a step in the right direction but without the application of suitable screening theory is impractical especially at this stage of non-standardization in design, topology, process control, material application, complexity, packaging, etc. Leading proponents in this school are D. I. Troxel and B. Tiger[6] of RCA and J. Partridge[7] of MIT Instrumentation Laboratory.

E. FALSE CATEGORIZATION SCHOOL

Several promising programs for deriving prediction information from extensive controlled testing have bogged down in misunderstanding and false categorization of test results. One such program developed much good test data for the Air Force by using unscreened parts that unfortunately resulted in multimodal data. Without recognizing the time character of the data and real lessons that could be learned, misleading conclusions were drawn. Four false categories of failure were devised to explain the apparently anomalous data. These categories were entitled:

1. "Time Dependent Process Failures
2. Mechanically Dependent Processes
3. Serial Effects
4. Parts that Never Worked (Escapes)."

When the description of these categories given by the authors are studied, it becomes obvious that too much unrelated information is included. Nearly all these categories are overlapping in several ways. For example, "Loss of Metal Adhesion" is listed as an instant effect under the category of Mechanically Dependent Processes. Usually this is a fatigue effect that is very time dependent and frequently serial in nature. Thus this one mode could rightfully be listed in three of the four categories. Many of the other items listed under "Instant Effects" are also highly time dependent. Part of the confusion apparently stems from lack of discrimination between methods of detecting final modes of failure and the nature of mechanism leading up to failure. Other examples of false categorization are the listing of "Mechanical Separation of Bonds" under "Serial Effects Category" and "Separation of Bonds" under "Instant Mechanically Dependent Processes Category." It is significant that when the authors try to utilize these false categories in modeling their test results, they abandon their theory and resort to a purely empirical reliability model which is a logical extension of the RADC Reliability Notebook version of the Hughes Type 1 interim models. Leading proponents in this school include D. C. Porter and W. A. Finke[8] of Boeing Aerospace Division.

F. COMPLEXITY INDEPENDENCE SCHOOL

From the observation that integrated circuit failure rates approach those of similarly screened simple semiconductors, the complexity independence school has derived a hypothesis of failure dependence between similar system elements exposed to certain critical environments. The degree of dependence is a function of the ratio of the variance in element strength to the variance in applied stress such that, if the latter is large compared to the former, system failure probability approaches that of a single element. In other words, functional or process complexity does not influence the reliability level. Therefore, it is concluded that once design, process controls, and screening procedures reach maturity, LSI chip reliability levels, exclusive of the package, will approach those of simple integrated circuits. Leading proponents of this school are A. M. Briepohl[9] of Sandia Corporation and B. E. Zimmerman[10] of Texas Instruments.

The large element of truth in this approach hinges for its immediate practicality around the phrase "once design, process controls, and screening procedures reach maturity." During the long interim before this statement is likely to become true for large scale LSI arrays, suitable prediction procedures are needed that will be based on complexity of design and manufacturing factors including screening status that markedly effect the probability of failure under any given set of stress and application conditions. It is not feasible at this time or in any early future period to make these simplifying assumptions. To do so oversimplifies the problem to an impractical state.

G. FAILURE RATES PER IDENTIFIABLE PHYSICAL UNIT SCHOOL

The failure rates per identifiable physical unit school believes that failure rates for identifiable failure modes can be normalized to some identifiable physical unit such as failures per bond. For hybrid LSI prediction this approach quantifies the effects of each failure mode active within each element of the microcircuit.

Certain elements may have a single predominant mode that determines its failure rate while others may have several contributing modes. Also, the relative contribution of each mode may change with the type of stress and its severity level.

In practice, a reliability prediction by this method becomes an engineering study of the paper design of the LSI, its manufacturing processing, inspection and control procedures, and screening during manufacture, plus details of the anticipated end use. A substantial degree of mature engineering judgement is required to complete successfully the following major steps in prediction:

1. Identify major elements of the LSI component such as oxide layers, metallizations (covered and uncovered), vias (feedthroughs), lead bonds, die-header bond, contact cuts, glassivation, chip, interconnecting leads, package, etc.
2. Quantify the number of each type of element
3. Analyze thoroughly each of the element types to characterize geometries, materials, interface combinations, etc.
4. Determine the potential failure modes for each element type based on knowledge of its physical characteristics, anticipated screening procedures, and end use stresses of load and environment

5. Estimate a failure rate for each element based on the above stresses and modes of failure
6. Total elemental failure rates into a combined LSI component estimate.

The key weaknesses of this approach are in steps 4 and 5. It is very common that false categorization of failure modes and conditions in these steps result in an unintelligible mass of data that requires astute engineering judgement to reduce and interpret. Proof of the validity of the judgement decisions is very difficult. However methods for making simplifying assumptions and emphasizing basic failure mode families make this a practical approach school. An improved example of this approach similar to the RADC Reliability Notebook method but updated for use with modern hybrid devices has been used successfully at Hughes for several years. Excerpts photographically reproduced of this from Hughes R-67-3 (Designers Reliability Handbook) are shown in Appendix B. Although this is an improved prediction method, the type of models employed are classed as interim models because they lump many application stress effects into adjustment K factors. Further improvements in these models to eliminate the need for K adjustment factors by use of basic stress parameters and to improve the methods of steps 4 and 5 give promise of feasibility sought by this project. Major proponents in this school have been L. D. Davis,[11] M. F. Adam,[12] and D. M. Aaron[12] of North American Rockwell Autonetics Division and C. M. Ryerson[13] of Hughes Aircraft Company. This report contains concepts and proposals which are an advanced form of this school.

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III. DATA REVIEW AND SUMMARY

A. SOURCES AND AMOUNT OF DATA

A major collection of microcircuit failure information has been compiled for the Air Force (RADC) by the Reliability Analysis Center (RAC) of the Illinois Institute of Technology (IIT). The code symbol for this source herein is RAC-IIT. Various classes of technology are represented by more than 20 billion device hours of microcircuit failure data. The bulk of this applies to the Bipolar, Junction Isolation Class IC's. Analysis and interpretations of this data are summarized in this section.

A second major source of data analyzed in this report is more than 5 billion part hours of microcircuit failure data unpublished by Hughes Aircraft Company. Much of this data are for hybrid LSI devices.

A third source of many billion part hours consists of direct reports from suppliers and users of microcircuits. Some of this information may already be included in the RAC-IIT data. An advantage of this direct information is that more detail of the part application, failure conditions, and failure mechanisms are given.

The fourth source of data with billions of part hours is the Navy FARADA data that give very little information about the failures or their mechanisms. Since many of the largest sources of data are Air Force reports, it is believed that most of this information is duplicated in the RAC-IIT summaries.

B. ANALYSIS CONCLUSIONS

1. General

Although much overlap is evident in the data from various data sources the source summaries and presentations are helpful in drawing various conclusions not affected by the overlap or which may benefit from it. For example the bulk of the RAC-IIT data applies to the Bipolar, Junction Isolation Class. Because of the overlap in data sources, this statement is probably accurate for LSI data in general. Other valid conclusions can also be made as explained in the following sections. Emphasis in the following discussion is on the general conclusions and not on the specific sources used. In fact, the most valuable conclusions could have been derived from data having sufficient detail from any of the sources.

2. Failure Mode Categories

One objective of this study was to analyze the rate of occurrence of specific failure modes. From the mass of RAC-IIT data, a total summary analysis was made by dividing the failure modes into 14 categories as shown in Table II. If the items for which the failure mode was recorded are plotted, the distribution is as shown in Figure 1. Here it can be seen that the a_4, a_3, and c_1 categories are major with all the others making a minor contribution. In terms of a "Pie" chart this result is shown in Figure 2. Here some of the categories are combined as shown on Table III. The data show that the quantities of bonding and defective chip problems are minor. This is not in line with other similar "Pie" charts which are found in the literature or which can be devised from Hughes and other sets of data. Some of these other failure mode distributions are shown in Figures 3 through 10.

A major contribution of this feasibility study has been to explain how differences such as these can exist in various published data and how this understanding can be used in the future to develop practical LSI prediction models. Raw data from the Hybrid LSI engineering facility at Hughes, Culver City, provided the insight needed for understanding this phenomena. Many thousands of hybrid devices have been manufactured here, and complete

TABLE II. FAILURE MODE CATEGORIES

Category	Fraction of Failures in percent (RAC-BP, J.I.)
Category a - Component Related	
1. Short circuit	0.33
2. Intermittent	0.07
3. Mechanical Degradation	4.11
4. Electrical Degradation	8.58
Category b - Workmanship or Process Related	
1. Contamination	0.42
2. Process Caused	0.56
3. Package and Seal	0.11
4. Oxide problems	0.60
5. Wire problems	0.24
6. Bonding problems	0.71
7. Die problems	0.37
Category c - Application, Use or Test Related	
1. Electrical Overstress	2.53
2. Mishandling	0 64
Category d - Unknown	
1. Not recorded, not specified. Not reported, etc.	80.72

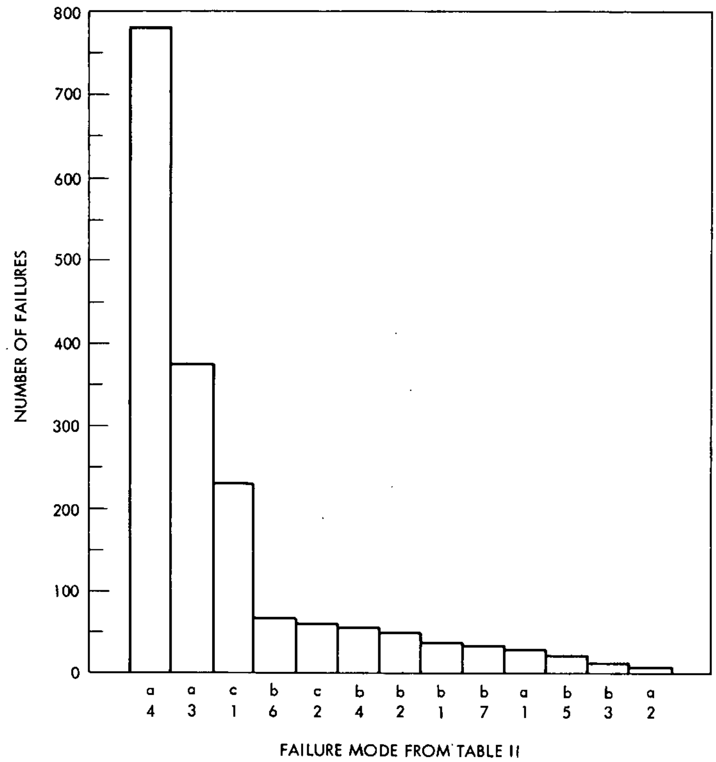


Figure 1. Bipolar, Junction Isolation, Totals (Distribution of Specified Failure Modes)

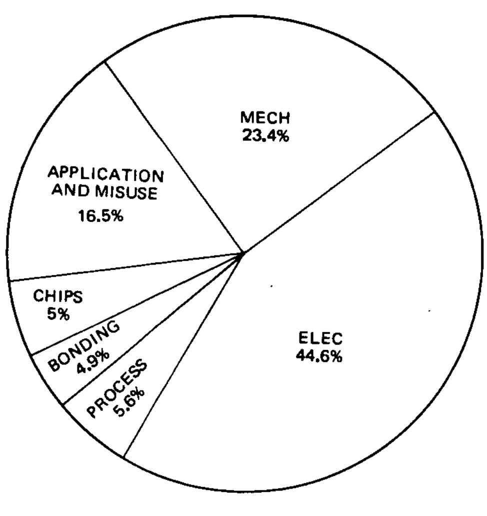


Figure 2. RAC-IIT Total Failure Modes (Bipolar, Junction Isolated)

TABLE III. COMBINED CATEGORIES OF RAC-ITT COMMON FAILURE MODES

Table II		Pie Figure 2			
Category	Percent	Percent of Total	Percent of Pie	Degrees	Category
a 1	0.33	4.51	23.4	84.5	Mechanical
2	0.07				
3	4.11				
a 4	8.58	8.58	44.6	160.1	Electrical
b 1	0.42	1.09	5.6	20.2	Process
2	0.56				
3	0.11				
b 4	0.60	0.97	5.0	18.1	Chip
7	0.37				
b 5	0.24	0.95	4.9	17.7	Bonding
6	0.71				
c 1	2.53	3.17	16.5	59.4	Application and Misuse
2	0.64				
Totals	19.27	19.27	100	360	All recorded

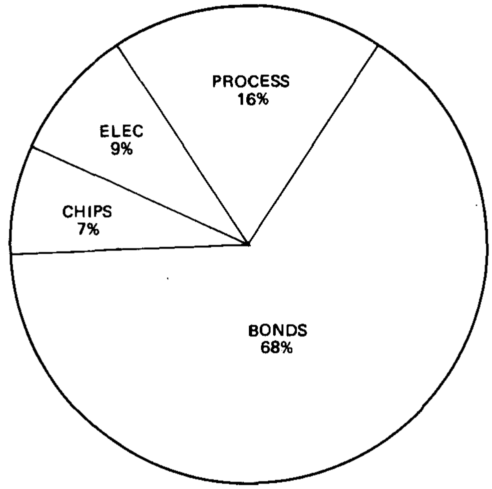


Figure 3. IBM Solid Logic Technology Hybrids (System/360)

TABLE IV. 100 MILLION HOURS (MOSTLY BURNIN AND EARLY LIFE) E.F. PLATY

Failure	Percent	Degrees
Bonds	68	245
Process	16	57.6
Electronic	9 } 16 percent	32.4
Chips	7 }	25. 2
Totals	100	360.2

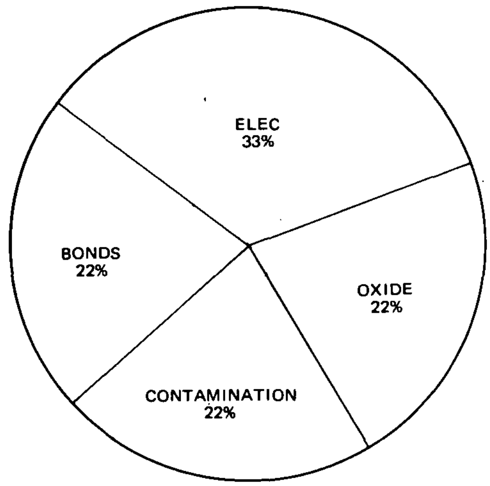


Figure 4. MOS-LSI Burn-In
L. Hamiter (Quality
Standards for LSI)

TABLE V. MOS (HAMITER QUALITY STANDARDS)

Failure	Percent	Degrees
Contamination	22.33	80
Oxide	22.33	80
Bonds	22.33	80
Electronic	33	120
Totals	100	360

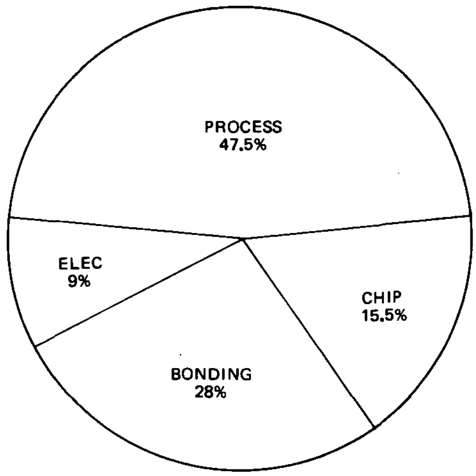


Figure 5. System Test

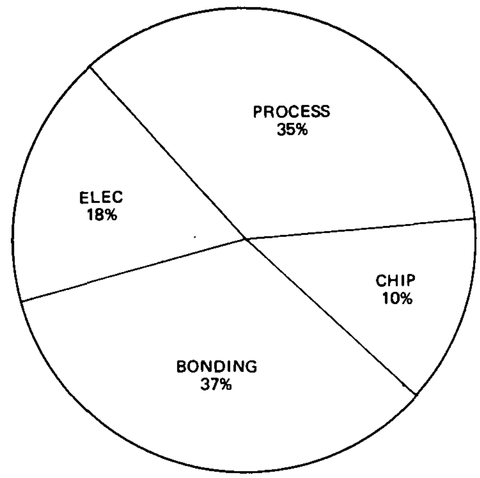


Figure 6. Environmental Test

TABLE VI. MINUTEMAN II IC R.E. MULFORD
TRW SYSTEMS INC.

Category	Code	Mode	System Test			Environment Test		
			Percent		Degrees	Percent		Degrees
Electrical Degradation	A	Parameter Drift	9	9	32.4	5	18	65
	U	Unknown				13		
Process	B	Diffusion, Mask etc	7			0		
	C	Pinholes, Oxide	8			21		
	D	Damaged Oxide	16	47.5	171	7	35	126
	F	Contamination	16.5			7		
	L	Package Seal	0			0		
Bonding	E	Bond to Terminal	4			6		
	G	Bond to Die	3	28	101	10	37	133
	H	Interconnection	9			0		
	J	Lead Bonds	12			21		
Chip	K	Die	15.5		55.6	10		36
Total			100		360	100		360

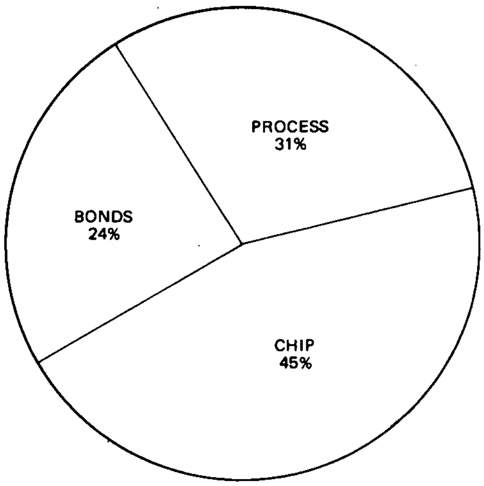


Figure 7. Precap Inspection

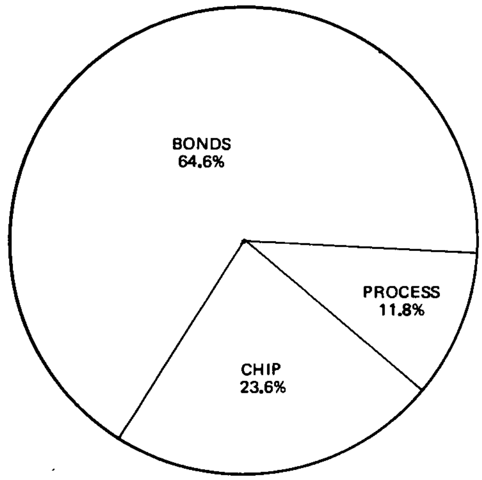


Figure 8. Post Cap Test

TABLE VII. HUGHES HYBRID MANUFACTURING (ENGINEERING FACILITY)

Failure Mode	Precap Inspection		Post Cap Test	
	Percent of Failure	Degrees	Percent of Failure	Degrees
Bonds	24	86	64.6	232.5
Chip	45	162	23.6	85
Workmanship and Process	31	112	11.8	42.5
Totals % of Failures	100	360	100	360

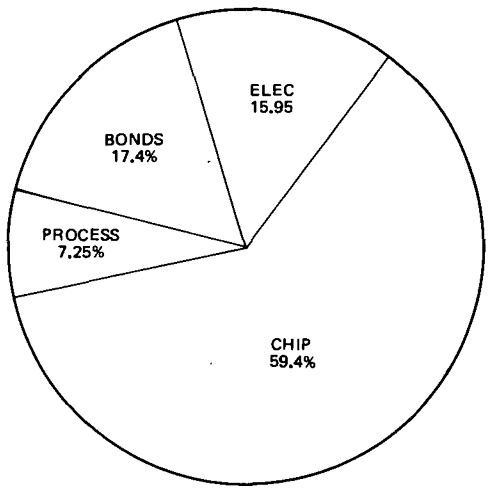


Figure 9. As recorded F-14.

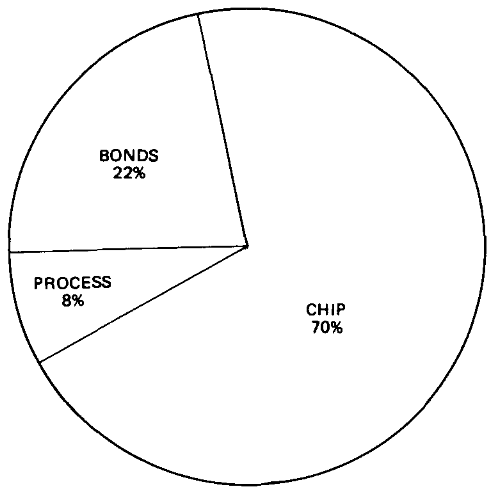


Figure 10. Harmonized F-14.

TABLE VIII. HUGHES - F-14 HYBRIDS DURING MANUFACTURE

Failure Mode	Figure 9 Recorded		Figure 10 Harmonized	
	Percent	Degrees	Percent	Degrees
Bonds	17.4	62.6	22	79.2
Chip	59.4	214.0	70	252.0
Workmanship and Process	7.25	26.0	8	28.8
Electrical	15.95	57.4	--	
Totals	100	360	100	360

records have been kept of each device including a detailed rework and failure history. The cause of failure has been determined for each failure event.

A random sample of the causes of failures occurring during hybrid LSI manufacturing reveals the pie distributions of modes as shown in Figures 7 and 8. A third pie distribution of failure modes that occurs during subsequent manufacture of a major system that uses many of these same hybrids is shown in Figure 9. Because these data were not taken with this comparison in mind, some discrepancy exists in the way that failure causes were identified. It can be seen that a fraction of the failures attributed to electrical degradation could have been assigned to the other three categories as is done using best engineering judgment in Figure 10. The intent here is to illustrate the principles involved and not to emphasize the preliminary numbers developed in this short feasibility study. The figures used should be considered as typical numbers derived from actual cases but not necessarily having high statistical confidence. This can be evolved later as the need arises to validate the parameters of the new prediction models to be developed. A considerably broader breakdown of failure modes will be used in the final prediction models according to the needs and capabilities described in this report. For example, in these illustrations the failures attributed to chips could actually be traced to multiple causes in the original chip manufacturers plant. Thus, depending on the coverage and use of the models, the total process and workmanship fractions can be much larger and retained with the separate identity of direct cause from earliest material assembly to final field use.

It should be indicated that the failure mode distribution shown in Figure 10 is typical of many distributions found for hybrid microcircuits at later stages of system life. In other words the distribution change is largely related to the impact of factory reliability screening. Its meaning as compared to reliability prediction is explained in the next section.

3. <u>Failure Mode Distribution Changes Explained</u>

A major accomplishment of this feasibility study has been the insight gained in the significance and methods for control of Failure Mode Distributions. It has been indicated that the literature abounds with data that can be illustrated in a variety of dissimilar failure mode distribution pie charts. Most of these have little value or meaning for use in making practical LSI predictions. It has been assumed that there should be a use for these representations of failure mode distributions, but until now the apparently inconsistent variability of failure mode plots from the same types of microcircuits has caused only confusion and uncertainty of their validity. Now it is possible to understand and make effective use of failure mode distributions for the prediction and control of LSI microcircuit reliability.

Several important conclusions on this subject are summarized below:

a. A major proof of the feasibility of LSI prediction models hinges on the new ability to explain why failure mode distributions will change from time to time and what the impact of these variations has on demonstrated reliability.

b. It is logical to expect changes in failure mode distributions with time during the manufacturing and screening cycles. These changes are evidence either that new failure modes are being generated (by process deficiencies or workmanship error) or that a gross screening process is underway. Some factory intervals will involve both phenomena. These can be measured and controlled to obtain inherent predictable reliability.

c. Accurate reliability prediction requires that the failure mode distribution remain constant after release of the system to use during the interval for which the prediction is made. This factor is controllable and depends on the stability of the product, its design maturity, and its reliability screening status. All these factors are now measurable, controllable, and predictable.

d. The failure mode distribution for any system or device becomes constant with stress-time only when no new defects are being generated and when a major portion of the incipient failure devices have been removed by reliability screening. Until this desirable maturity is achieved, any increase or change in the type of stress can appreciably alter the failure mode distribution.

e. Each type of failure mode constitutes a subpopulation with its own inherent resistance to detection and its own characteristic degradation from stress with time. Whenever the failure mode distribution changes with applied stress-time, some failure modes are indicated as being incited to failure by the stress at a faster time-rate than are others. If any mode is failing at a proportionally higher rate than others, this signifies that the items in this subpopulation are numerous and considerable reliability screening may be required.

It is obvious that any single mode could not continue indefinitely to fail at a proportionally higher rate than the others. Sooner or later in such a case the supply of incipient failures in that mode becomes exhausted or diminished to a failure rate level commensurate with the relative complexity of that mode in relation to the failure chances inherent in the design.

During screening the failure modes with the higher probability of failure are removed at a high but decreasing rate. This rate decreases rapidly until the magnitude of their detection distribution tail flattens out and approaches a minimum random failure rate for each mode. This mode is proportional to the stresses applied and to the relative design complexity of the elements associated with each mode. From this time on to the end of useful life, the failure mode distribution remains relatively constant as long as the use stresses remain similar or an equivilent combination of stresses.

f. A corollary or parallel axiom is that until the relative failure mode distributions (Pie Plots) become unchanging with time for a given stress load, it is proof that reliability screening has not been completed for application at those stress levels.

g. Another axiom is that any single pie plot of failure modes for a given microcircuit is meaningless alone. Throughout the life history representing the manufacturing and screening periods of the device and until the mode distribution becomes constant with time, the distribution of failure modes will be different at each milestone of test as a function of the relative failure probability of the different modes.

This dependence of failure modes on their relative complexity and probability of failure can be illustrated by considering two oversimplified "ideal" cases. Consider first an ideal LSI that consists only of bonds. If this device were practical, only one general mode of failure could be shown on the pie chart throughout its life history. If only bonds existed then only bonds could fail. Next extend this "ideal" concept to a hybrid consisting of equal quantities of chips and bonds each having an equal chance of failure from the stresses applied. Throughout the life of these simple devices the pie plot failure mode distribution would average 50 percent bond and 50 percent chip. In any normal case (not ideal), the relative probability of failure for several modes will depend on similar factors of complexity and the subpopulation of incipient failures likely to occur with time stress and detection in each mode. In other words the status of reliability screening at any time and thus the relative probability of different modes occurring depends on the quantity of incipient defectives in each mode, and the ability of applied time-stress influences to incite failure events to occur in each mode, plus the ability of the test experiment to detect the failures when they occur.

The impact of the applied stresses on the failure mode distribution can be illustrated by another ideal case representation. Suppose that the real quantity of undetected failure modes in a lot of hybrids before screening were equally assignable to three failure mode categories:

1. Bond Failure,
2. Process or Workmanship Error
3. Electrical Chip Degradation.

(This example assumes higher than customary knowledge of true conditions to make the point.) This population to be screened is divided randomly into three equal groups, and each group is subjected to a different screening stress.

The group subjected to short time high vibration would experience: (1) a high percentage of bond failures, (2) few failures attributable to other types of process or workmanship defects such as scratched conductors, and (3) because of the short time and no electrical stress applied few or none of the electrical degradation type. The group subjected to long time electrical loading stresses would reverse these proportions and show a preponderance of the electrical degradation type defect. The third group subjected to screening consisting of many cycles of thermal cycling from very cold to very hot would likely show a preponderance of process and workmanship type defects. Note that the three pie charts illustrating the failure mode distributions for the three portions of this same lot would bear little resemblance to one another. In any actual case the interacting effects of probability of failure and applied stress can cause similar variations in pie plots of failure modes.

The third subject of detection efficiency is also important. Evidence indicates that much variation in published failure mode distributions is caused by differences between data source detection ability. Failures or defects not detected at any early stage reduce the failure rate observable in early time and cause a corresponding increase later when they are detected.

In addition, at any time interval the effectiveness of the detection instrumentation may not be uniform for the various failure modes. Investigation of these variations reveals that actual detection efficiency for any failure mode at any time and source can vary from less than 10 to more than 90 percent.

Another factor that causes much confusion in interpretation of failure mode distribution data is the changing definition of mode. For example, a failure cause that is basically process or workmanship oriented in the hybrid manufacturers plant is frequently listed as a chip defect when it finally becomes detected in the system manufacturers or part users plant. The definition changes as the orientation of the analyst changes.

When all these factors are considered, a reasonable expectation is that typical trend of failure mode distribution throughout the hybrid life will change as shown in Figure 11. Here the actual failure mode distribution plots of Figures 7, 8, and 10 for various stages of hybrid manufacture and use are supplemented with other typical distributions to reveal a characteristic life cycle progression. The life test distribution is a summary from the RAC-IIT data drawn intending to be typical of average characteristics during middle periods of service life.

The characteristics of this progression shown in Figure 11 can be observed and described as follows:

1. Poor bonds are difficult to detect visually or by simple electrical tests at the precap stage. Thus the obvious process and chip defects predominate in the first distribution.
2. The poor bonds not previously detected are caught by burn-in and other screening tests at the postcap stage and thus predominate in the second distribution.
3. Card Conditioning is performed after the hybrids are assembled onto electrical circuit cards. This step catches many partially failed bonds that escaped earlier detection plus-defects of various kinds representing degradation caused by the assembly operation.

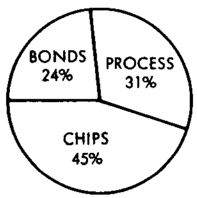
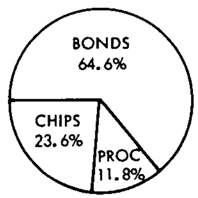
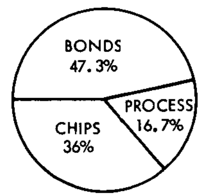
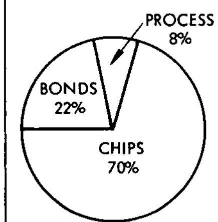
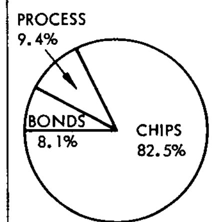
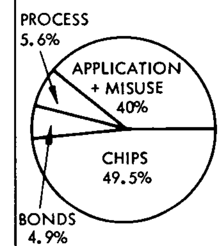
MILESTONE	PRECAP		POSTCAP		CARD CONDITIONING		SYSTEM MANUFACTURING		AGREE DEMO TEST		LIFE TEST	
FAILURE MODE DISTRIBUTION												
SOURCE	FIG. 7		FIG. 8		TYPICAL		FIG. 10		TYPICAL		RAC-IIT	
FAILURE MODE	PERCENT	DEGREES	PERCENT	DEGREES	PERCENT	DEGREES	PERCENT	DEGREES	PERCENT	DEGREES	PERCENT	DEGREES
BONDS	24	86	65	232.5	47.3	170	22	79.2	8.1	29.2	4.9	17.8
CHIPS	45	162	23	85	36	130	70	252	82.5	297.0	49.5	178
PROCESS & WORKMANSHIP	31	112	12	42.5	16.7	60	8	28.8	9.4	33.8	5.6 A 40	20.2 144
TOTALS	100	360	100	360	100	360	100	360	100	360	100	360

Figure 11. Characteristic Life Cycle Progression

4. The major shift in distribution caused by system manufacture reflects the shift in definition that now classifies many defects as chip problems. These problems might have been considered process or workmanship error had they been detected earlier by the hybrid manufacturer. In addition, the combined total stress time applied during the manufacturing and assembly operation has caused the degradation of many incipient but unfailed chips to degrade to the extent that the failure incipiency is detectable.
5. The AGREE demonstration test comes after most gross quality defects have been removed by prior screening efforts. Thus although the total quantity of failures is low, a large portion are diagnosed as chip defects. These failures have escaped prior detection but under the combined total time-stress of manufacture and demonstration have become detectable failures.
6. By the time most systems reach life test or can experience extended life in the field, they have become screened of most of their incipient early failures. As indicated earlier, systems that are thoroughly screened will exhibit constant failure mode characteristics with time for the stress conditions as screened. Thus thoroughly screened systems will exhibit similar failure mode distributions at subsequent 1000 or other time intervals. The failure mode shown in the sixth distribution of Figure 11 that was summarized from RAC-IIT field failure data can be considered typical of most subsequent life test data.

4. Relating Failure Mode Distributions to Fraction Defective

Most of the many factors just described have been under study at Hughes for several years. The impact and interaction of these factors have been modeled successfully in the development of eight series of models as previously described. Without deriving any of these models in this report, some are used here to relate failure mode distributions at the various milestones to the fraction of defectives remaining at any time and likely to fail under given use stresses. The previous discussion referred several times to the incipient failures in each lot. These have been given the code symbol "q" referring to that fraction defective in every lot this is not initially detectable but that degrades to a detectable defective condition under the influence of time and stress in manufacture, screening, test and use. In addition to these initially undetectable defects, a fraction of the lot comprises quality defects which though detectable have escaped detection up to the start of any time interval in the hybrid life cycle. This fraction of detectable quality defectives has been given the symbol "Q". Thus the total fraction defectives at the start of any interval can be written as the sum of the detectable and incipient undetectable defects, $(Q_o + q_o)$.

Since defects can be generated during a factory interval by process deficiencies or workmanship error, the peak detectable defects existing during any interval consist of the detectable quality defects present at the start of the interval (Q_o) plus the escaped fraction of the undetectable reliability defects $(\overset{o}{q_o})$ that have become detectable during previous intervals but for lack of 100 percent detection efficiency (D) have escaped detection, plus the detectable quality defects generated by the workers $(\overset{G_w}{Q_i})$, plus the detectable quality defects generated by the process deficiencies $(\overset{G_p}{Q_i})$.

$$\text{i.e.,}\ \overset{\text{Peak}}{Q_i} = \left(\overset{o}{Q_o} + \overset{o}{q_o} + \overset{G_n}{Q_i} + \overset{G_p}{Q_i}\right)$$

Also the peak or total undetectable reliability incipient failures existing during the interval consists of the initial fraction of undetectable incipient failures $(\overset{D=1}{q_o})$ existing at the start of the interval plus the undetectable reliability defects generated by the worker $(\overset{G_w}{q_i})$ and the process $\overset{G_p}{q_i}$, respectively.

$$\text{i.e.,}\ \overset{\text{Peak}}{q_i} = \left(\overset{D=1}{q_o} + \overset{G_w}{q_i} + \overset{G_p}{q_i}\right)$$

Note that these q_i defects become detectable as they degrade to the threshold of detection under the influence of stress with time.

These and other relationships existing between the initial, the peak interval, and the final fractions remaining at the end of any stress interval can be illustrated as shown in Figure 12.

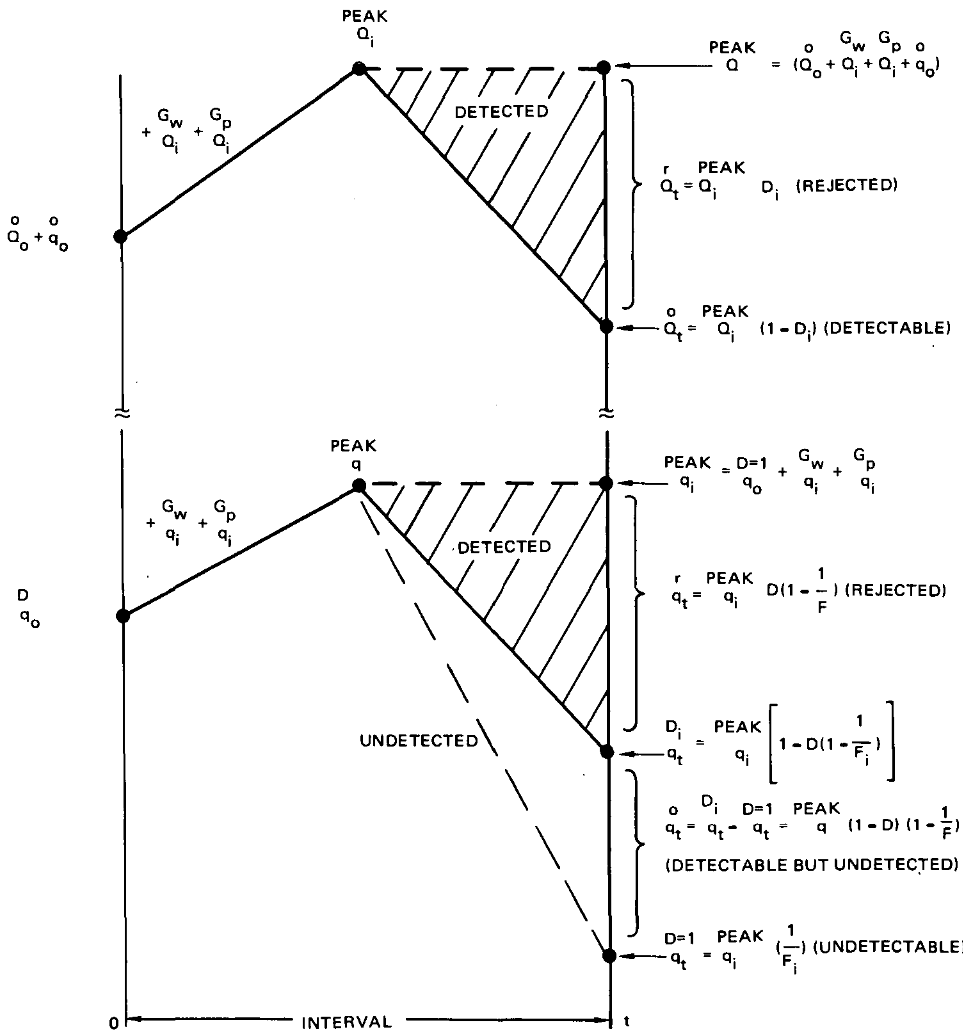
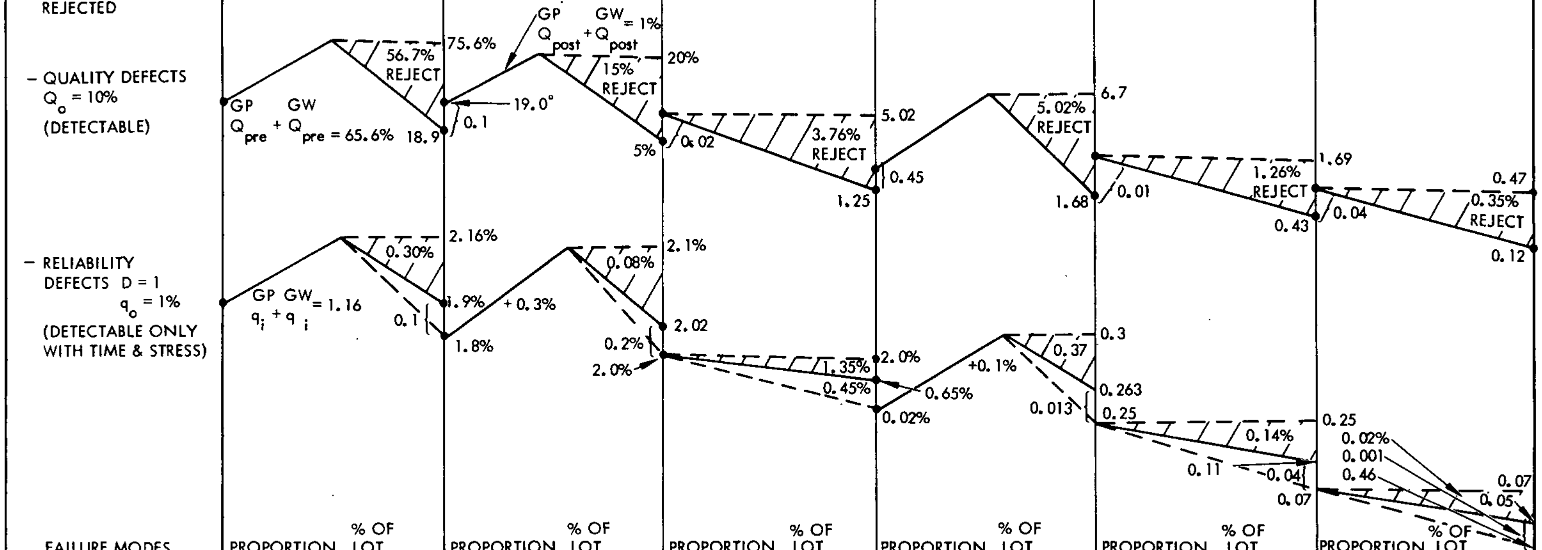


Figure 12. Combined Interval with Generation and Detection

These relationships and models have been used in this feasibility study to relate the conditions at each of six intervals during the hybrid life cycle. Actual reject percentages and other factors from the Hughes Hybrid manufacturing facility and system manufacturing experience have been used as shown in Figure 13. From the failure mode distributions of Figure 11 and the total failure rejects detected during each life cycle milestone the percentage of each lot defective in each mode was computed as shown in the tabular data at the bottom of Figure 13. These figures cross-check realistically with actual failure analyses summaries. They can be plotted to show

GIVEN CONDITIONS	PRECAP	POSTCAP	CARD CONDITIONING	SYSTEM MANUFACTURING	AGREE TEST (DEMONSTRATION)	LIFE TEST (1,000 HRS)
– SCREENING STRENGTH (Fi)	$F_{Pre} = 1.2$	$F_{Post} = 1.05$	$F_{cc} = 10$	$F_M = 1.2$	$F_A = 3.5$	$F_T = 1.5$
– DETECTION EFFICIENCY (Di)	$D_{Pre} = 0.75$	$D_{Post} = 0.75$	$D_{cc} = 0.75$	$D_M = 0.75$	$D_A = 0.75$	$D_T = 0.75$
– INTERVAL DEFECTS REJECTED	57%	15%	5.11%	5.05%	1.4%	0.37%



FAILURE MODES	PRECAP PROPORTION	PRECAP % OF LOT	POSTCAP PROPORTION	POSTCAP % OF LOT	CARD CONDITIONING PROPORTION	CARD CONDITIONING % OF LOT	SYSTEM MANUFACTURING PROPORTION	SYSTEM MANUFACTURING % OF LOT	AGREE TEST PROPORTION	AGREE TEST % OF LOT	LIFE TEST PROPORTION	LIFE TEST % OF LOT
BONDS	24	13.7	65	9.7	47.3	2.42	22	1.11	8.1	0.11	4.9	0.018
CHIPS	45	25.6	23	3.5	36	1.84	70	3.54	82.5	1.16	49.5	0.18
PROCESS & W	31	17.7	12	1.8	16.7	0.85	8	0.40	9.4	0.13	5.6 A40.0	0.02 0.142
TOTALS	100	57	100	15	100	5.11	100	5.05	100	1.4	100	0.36

Figure 13. Actual Hybrid Life Cycle Model
(not to scale)

the fraction-of-lot failure trend for each mode as in Figure 14. Notice how parallel the curves become in later milestone zones after screening is nearly completed.

5. Using Model Factors to Predict Reliability

Given the conditions of Figures 13 and 14, failures that would occur in a second thousand hours of life can be predicted. The first step in making this prediction should be to consider the stress and detection

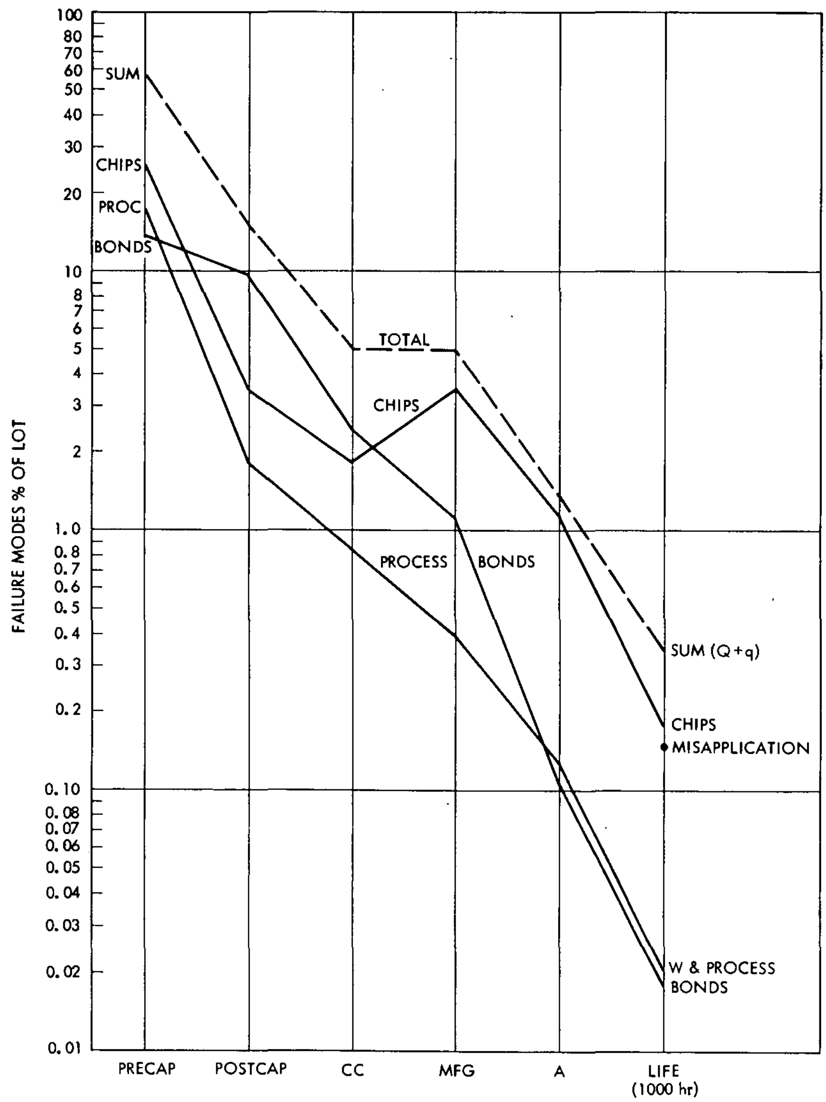
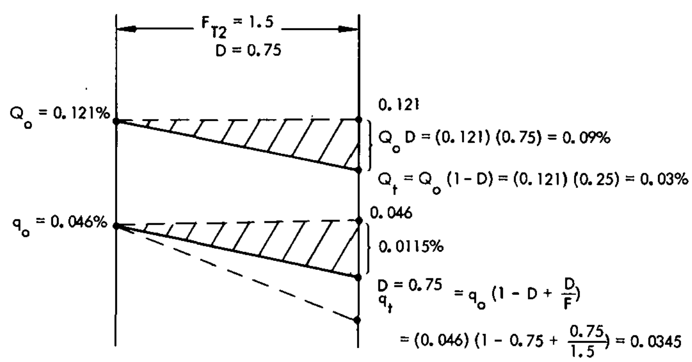


Figure 14. Fraction of Lot Failure Trend

conditions that will exist during the use time interval in question. The closer these can be determined by measurement or estimation, the more accurate the prediction will be. For illustration purposes, assume that the same stress and detection conditions will apply during the second 1000-hour life period as in the first. From this the screening strength F_{T_2} = 1.5 and the detection efficiency D = 0.75. On the basis that screening is now completed, the same failure mode ratios can be assumed. The problem can be set up for solution as in Figure 15.



THE TOTAL $Q_i + q_i$ DETECTED = 0.09 + 0.0115 = 0.101%

THE TOTAL QUANTITY FAILING OUT OF 200 HYBRIDS = 0.202

THE PROBABILITY OF SYSTEM CONTAINING 200 HYBRIDS SURVIVING SECOND 1,000 HOUR LIFE IS:

$P_s = e^{-0.202} = 81.7\%$

THE λ FAILURE RATE PER THOUSAND HOURS IS 0.101%/1000 HOURS OR 0.01 FAILURES PER 10^6 HOURS DURING THE SECOND 1000 HOURS OF LIFE

THE FAILURE MODE DISTRIBUTION WILL BE:

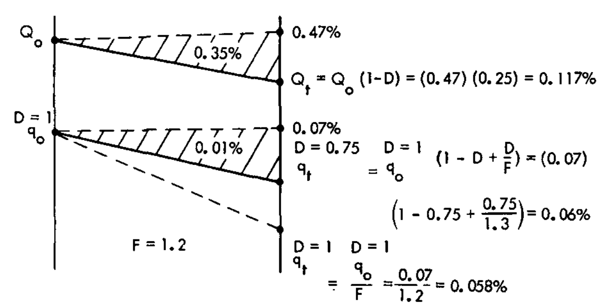
FAILURE MODE	PROPORTION	% OF LOT REJECTED
BONDS	4.9%	0.0049
CHIPS	49.5%	0.0499
PROCESS	5.6%	0.0056
MISAPPLICATION	40.0%	0.0404
TOTALS	100%	0.101

Figure 15. Prediction Problem No. 1
(Second 1000 Hour Life Period)

A requirement might be to predict the likely failure rate during the first one thousand hours of life if much milder application conditions were involved. Suppose less vibration, lower temperatures and less severe thermal cycling were imposed so that the screening strength over the 1000-hour period could be computed at $F_{T_1} = 1.2$ instead of the original 1.5. This problem can be solved and the predictions made as in Figure 16.

Comparison of this λ with that from the second thousand hours of life shows that there is a decreasing failure rate during the first few thousand hours of life thus the assumption of a constant failure rate after the AGREE test would be in error. Also the assumption that the failure mode distributions will be constant during these life periods is only an approximation. The errors caused by these assumptions are not large in many cases but to evaluate their magnitude on each program would require a study of the type developed on this contract. The advanced basic hybrid models proposed would eliminate the need for these assumptions.

In both these prediction examples the solutions have been found using assumed values of the screening strength (F_s) which can be computed from a derived empirical fit model shown in Table IX. This model is derived in



THE TOTAL DETECTED AND REJECTED = (0.35% + 0.01%) = 0.36%

THE TOTAL QUANTITY FAILING OUT OF 200 HYBRIDS = 0.72

THE PROBABILITY OF A SYSTEM CONTAINING 200 HYBRIDS SURVIVING THIS FIRST 1,000 HOUR LIFE IS:

$P_s = e^{-0.72} = 49\%$

THE λ FAILURE RATE PER THOUSAND HOURS DURING THIS FIRST 1000 HOURS OF LIFE: λ = 0.36%/ 1000 HRS

Figure 16. Prediction Problem 2 (First 1000 Hour Life with Different $F_{T_1} = 1.2$)

TABLE IX. SCREENING STRENGTH F_s MODEL

$$F_{s_i} = \frac{1}{(1-P_{f_T})(1-P_{f_{dT}})(1-P_{f_v})}$$

Where:

P_{f_T} = is the probability of failure due to temperature.

$P_{f_{dT}}$ = is the probability of failure due to time rate of change of temperature during cycling.

P_{f_v} = is the probability of failure due to vibration.

And the functions are:

$$P_{f_T} = \frac{q_T}{q_o}\left[1 - e^{-\psi S_T \sum_i t_{s_i} e^{-A/T_s + 273}}\right]$$

$$P_{f_{dT}} = \frac{q_{dT}}{q_o}\left[1 - e^{-\psi \sum_i (S_T + S_{dT}) t_{dT_i} e^{-A/T_{E_{dT}} + 273}}\right]$$

$$P_{f_v} = \frac{q_v}{q_o}\left[1 - e^{-\psi \sum_i (S_T + S_v) t_{v_i} e^{-A/T_{E_v} + 273}}\right]$$

$\frac{q_T}{q_o}$ = is the fraction of the total q_o screenable by temperature alone

ψ = is the number of repetitive stress cycles

S_T = is the temperature stress screening constant

t_{s_i} = is the duration time (hours) of each temperature

T_S = is the effective operating temperature = $|T_{op}|$

A = is the Arrhenius degradation constant which is a function of activation energy (ν), the charge on an electron (q_e), and Boltzmans Constant k (i.e. $A = \frac{q_e \nu}{k}$)

$\frac{q_{dT}}{q_o}$ = is the fraction of the total q_o screenable by thermal cycling with temperature

S_{dT} = is the thermal cycling stress screening constant

$T_{E_{dt}}$ = is the effective cycling degradation temperature i.e. $\left(T_{E_{dt}} = \frac{|T_{u_i} - 25| + |T_{L_i} - 25| + 50}{2} \text{ in } ^\circ C\right)$

t_{dt} = is the duration (hours) of each time rate of change

$\frac{q_v}{q_o}$ = is the fraction of the total q_o screenable by vibration with temperature

S_v = is the vibration stress screening constant

T_{E_v} = is the effective vibration degradation temperature i.e. $\left(T_{E_v} = |T_{op} - 25| + 25 \text{ in } ^\circ C\right)$

Appendix A. Its use in the manner of the examples is a valid new prediction technique. However it is believed feasible to develop an accurate screening strength model for each of the basic failure modes. This development would provide for more accurate predictions without the assumption that screening is complete and that failure mode distributions will remain constant. A discussion of basic modeling theory in Section D introduces this proposed development. Until this development can be completed, successful predictions can be made by using the established Hughes interim hybrid prediction technique.

6. The Hughes Interim Hybrid Prediction Technique

This study has established the feasibility of developing new models and a prediction technique for predicting hybrid reliability without the use of k factors for combining general application stresses and without the need for several assumptions such as screening status and constancy of failure mode distribution with time. Until this advanced more basic technique can be perfected, it will be possible to make approximate hybrid predictions using the Hughes Interim Hybrid Prediction Technique. This is an improved form of the integrated circuit technique released by Hughes in the 1967 updating of the RADC Reliability Notebook. It is based on an interim type model involving a base failure rate λ_b that is a function of the design, structure and process, modified by a series of π product terms. This Hughes Hybrid Failure Rate Model is

$$\lambda_H = \lambda_b (\pi_E \times \pi_T \times \pi_Q)$$

where:

π_E is an environmental factor found from a convenient table.

π_T is the base or junction temperature factor formed from a plotted curve

π_Q is a quality modifier chosen from a table to reflect the screening conditions and procurement specification requirements.

$$\lambda_b = A_s \lambda_{sub} + A_s \lambda_c + N_{PC} \lambda_{PC} + \lambda_{PF} \pi_{PF} + \Sigma N_{RT} \lambda_{RT} + \Sigma \lambda_{DC} N_{DC} + \Sigma \lambda_{cp} N_{cp}$$

$A_s \lambda_{sub}$ = the hybrid circuit substrate failure rate and is computed as 0.001 percent/1000 hours times the area of the substrate in square inches. If the actual area of the substrate is unknown, use 50 percent of the external package area or 0.2 inch less than dimensions, whichever is greater, to compute the area of the substrate.

$A_s \lambda_c$ = the failure rate contribution due to the network complexity. The values are found in Figure 26 (appendix B) as a function of the number of separate conductive areas (resistors and conductive paths plus the number of interconnect wires) per square inch of substrate. Assume two interconnect wires for each transistor chip, one for each diode chip, and one for each external connection for ICs unless details to the contrary are available.

$N_{PC} \lambda_{PC}$ = the number of screen and fire cycles required to form the thick film pattern on the substrate or the number of mask-etch cycles required to form the thin film network pattern on the substrate times 0.004 percent/1000 hours which is the failure rate term for each cycle used in manufacturing the hybrid. If number of cycles is unknown, assume three cycles.

$\lambda_{PF} \pi_{PF}$ = the hybrid microcircuit package failure rate which is a function of the package style or configuration and the materials used in its construction.

where:

λ_{PF} = 0.002 percent/1000 hours (a normalized value of base failure rate for all hybrid microcircuit packages).

π_{PF} = an adjustment factor that modifies λ_{PF} as a function of the package style and the materials used in its construction. The values of π_{PF} are tabulated in Table 65 (appendix B) for various combinations of style and material.

$\Sigma N_{RT} \lambda_{RT}$ = the sum of the additive failure rates for each resistor as a function of the required resistance tolerance.

N_{RT} = the number of film resistors of a given tolerance.

λ_{RT} = the failure rate to be used for each resistor of a given tolerance as specified in Table 66 (appendix B).

$\Sigma \lambda_{DC} N_{DC}$ = the sum of the discrete chip device failure rates for semiconductor, IC and capacitor chips. The failure rate is computed as shown in Table 67 (appendix B).

$\Sigma \lambda_{cp} N_{cp}$ = the sum of the failure rates of the conventionally packaged devices used in construction of the hybrid microcircuit (glass packaged diodes, molded resistors or capacitors). Until more information is available chip resistors should be treated as their equivalent in leaded discrete devices. The failure rate is obtained by computing the failure rate in the normal manner at 25^{o}C, excluding the environmental factors π_E and Σ_E.

Note: This Hughes Interim Hybrid Prediction Technique is explained in detail with application examples in Appendix B.

Proof of the success of this interim modeling prediction technique is the results obtained on the F-14XN3 program. There are 545 Hughes hybrids used in each of the XN3 systems. To date these systems have logged in excess of 3, 700, 000 hybrid device hours in approximately 4600 system hours. A decreasing failure rate was observed with time. During the first 1600 hours, 17 failures occurred yielding a failure rate of 2 percent per 1000 hours. In the next 3000 hours, nine failures were experienced for a failure rate of approximately 0. 5 percent per thousand hours. Deleting five failures considered to be non-relevant (misapplication corrected through test or design modification) the average failure rate achieved during the above 3000 hour interval computes to 0. 24 percent per thousand hours. Note that this was predicted at 0. 28 percent last year by use of the Hughes Interim Hybrid prediction technique. Note also that the preliminary gross numbers used in the proposed new technique described in Section 2e also netted figures close to these of 0. 36 percent and 0. 2 percent per thousand hours for two consecutive

1000 hour intervals. It is believed that this new technique when finally perfected will provide for accurate predictions plus direct correlation with design, factory, process, and screening, control and cost factors. Whereas the interim technique predicts the bottom of the Reliability Bathtub curve after this has been reached, the new basic modeling technique will predict the failure rate and other related factors for any time interval down to the bottom of the reliability bathtub curve and can predict when the bottom will be reached.

A third modeling technique, developed for NASA Goddard specifically for use with semiconductor diodes, applies also to hybrid microcircuits later in life when the combined influences of temperature, load and radiation cause a degradation characteristic typical of the conventional wearout portion of the reliability bathtub curve. This can be explored more fully in a later modeling effort. The success achieved with this third technique in a controlled experiment further emphasizes the feasibility of the proposed modeling effort. The two techniques involve compatible models, terminology and failure mode postulates. They supplement and complement one another and when finally perfected will permit accurate prediction of total life cycle reliability and cost for complex microcircuit systems. Additional information on the feasibility of the wearout models and life cycle cost tradeoffs using the models can be provided on request.

IV. PREDICTION MODELING THEORY

A. GENERAL

Recent advances in prediction modeling theory now make it feasible to develop accurate reliability prediction models for use with LSI microcircuits and large scale hybrid arrays. Analysis of past modeling efforts in the field of reliability prediction has revealed error in approach, philosophy and technique, and has identified not only the methods of modeling most likely to be successful but has revealed pitfalls to be avoided. In particular, a serious study has been made of the tendency for most mathematical models to be mathematically rigorous but too complex and unwieldly for practical application to complex microcircuit or equipment systems. Major breakthroughs in theory and approach have resulted. These advances now make it possible to tradeoff program emphasis at any point on such factors as design goals and controls on materials and factory operation in response to specific information on the net result to be expected in terms of total life cycle cost and achieved reliability at any interval during manufacture and life.

Many of the past problems in reliability have been caused by the "lack" of proven technological methods and criteria for support of management decision making. Characteristic of this "lack" has been that for the past two decades Reliability Engineering has limped along on the strength of only one "law" of reliability, the so called "law" of exponential failure probability. With all its inadequacies, this law has served well within its restricted meaning and limited scope of application. But for lack of anything better, most aspects of program control and cost optimization have had to obey undefined proprietary laws of immediate self interest, approximation by those not necessarily the best qualified, and individual intuitive judgement often based on partial facts and incomplete information.

It is believed that most of the basic technical tools needed for the economic controlled achievement of specified high system reliability have now been developed. The detailed definition of the real world parameters that affect cost and reliability achievement makes these tools new and unique. Another key aspect of this new approach is the formulation of workable mathematical models that provide for specific cost and reliability tradeoffs.

In broad perspective these new models and variant equations are expressions of order, cause and effect derived from past engineering and program experience. Briefly, they are mathematical patterns of dynamic results, expressing the interaction and synergistic effects for statistical averages of aggregate stress, strength, and strain factors reacting against one another and against inherent activation energy thresholds. In other words, they constitute plausible probability distributions that express composite processes of nature corresponding to physical observations of stress and failure phenomena in real time.

During most attempts in the past to model reliability characteristics, the meaning and impact of the many key or basic stress and strength parameters were not defined. Without these definitions, the reliability models could only show the classic shape of known statistical distributions without revealing the basic interaction effects in the degradation mechanisms. For example, it has been possible to show that under certain conditions a Weibull distribution would fit certain failure data; however, no real insight was provided into what could be done by management to change the distribution or relate it to its causative factors. A further illustration is that the shape parameter β of a Weibull cumulative failure probability distribution has never been recognized as in itself a measurable function of manufacturing quality, screening effectiveness, item strength figure of merit, and stress loading. When these functions become defined (as they have been recently for many types of systems, parts and circumstances), the effect on reliability and the cost of changes in these basic parameters can be predicted. Hence for the first time it is now possible to relate program plans, conditions, and controls to reliability results and specific costs.

The following discussion includes detailed system and program application theory in the belief that the feasibility of LSI prediction models hinges on their applicability and compatibility with the total system procurement and life cost problems.

B. NEW MODELING APPROACH

The primary function of math modeling is to express the processes of nature in mathematical form showing the operational relations between variables and parameters so that apparently diverse and obtusely related phenomena can be understood. A good model will reduce great quantities of experimental data to simple mathematical form without loss of meaning and with greatly increased visibility of important principles and interactions.

Unfortunately most processes of nature are so complicated that it is frequently impossible to develop tractable mathematical formulae that correspond exactly to the physical reality. Generally, many distinctive mechanisms lead to failure modes of many kinds. When terms in a model are generated for each of these modes and mechanisms, the models become very complex and impossible to solve or use effectively. This is true even for some discrete components and particularly so for complex systems.

As a result, except for cases of simple systems involving only one or two material interfaces, math models rightfully have earned a reputation of general impracticality. All too often the model was either too complex to have practical application or it was a simple explanation of very limited phenomena that were not system oriented.

After years of working with this common approach to modeling, it was recognized that it is a self-frustrating exercise to try to model the degradation effect of stresses applied to every failure mechanism in a system. A new approach was needed.

The first major breakthrough came in the definition of "Basic Family Failure Modes." The emphasis was shifted from the type of mechanism and its final failure mode to common characteristics of response by groups of mechanisms reacting to the applied stresses. By definition a basic family mode includes all degradation and failure mechanisms that can be modeled by a common failure distribution. In other words, the common response characteristics categorize a basic family mode, not the distinctive nature of an individual mechanism.

The value of this new approach can be appreciated when the problems of modeling for complex systems are considered. For example, consider the case of a microcircuit that is a miniature complex system. The quantity of distinctive failure mechanisms in LSI microcircuits may exceed several hundred. A model with several hundred terms is impractical. However, when it is realized that the response of all several hundred mechanisms can be modeled by only six or seven different degradation distribution curves, the concept of basic family modes takes on major significance. All the mechanisms that react the same way to a set of combined conditions can be considered as belonging to a common category or basic family mode. The total system response thus can be modeled successfully using only as many terms as there are basic family distributions that describe the stress-time response.

For clarification it can be stated that say 20 percent of the failure mechanisms will obey a family mode cumulative failure distribution in time; another percentage (say 15 percent) will obey a second basic mode failure distribution in time, etc. Such a model containing six or seven terms can be validated in simple (economic) tests and then applied easily for practical program control. Other guidelines, such as recognition of the differences between the effect of stresses on chemical properties and micro-structure and their effects on mechanical properties and macrostructure, simplified the derivation and application of the new models and laws.

From such derivation and with proof by empirical fit to various program data, a total of eight different series of models have been developed relating to a dozen or more useful new reliability "Laws". Many other related equations representing different forms or variations of the Law relationships are also helpful for making specific computations and for revealing stress-strength interactions. These models and equations represent a continuous theory relating the physical chemistry of composite materials and their applied dynamics in complex devices with the device degradation and failure characteristics. This continuous theory provides mathematical bridges between the various reliability concepts that previously could not be related or expressed in simple and practical mathematical models.

In brief summary, this theory relates to the fact that nearly all materials are unstable with increased temperature and undergo a chemical breakdown or thermal degradation that obeys a time-rate process. A parallel fact not generally recognized is that nearly all strength characteristics in resistance to any other stress and stress-to-stress synergistic effects also obey a rate process in the time-stress continuum. Thus all aspects of strength in time can be related to the specific degrading stresses in a practical model or algorithm that describe real-life degradation conditions. When these rate processes for all the interacting stresses and strengths are combined in a model commensurate with the real world combination of physical conditions and reaction thresholds, a workable engineering characterization or "Law" results. Probable failure rates, quantities of failure likely to occur during specific stress intervals, the percent reliability defectives remaining undetected at any time, and all the other factors listed in Table X thus can be clarified and numerically evaluated as needed by the program controls and requirements.

Effective cost control derives from the ability to compute specific changes in numerics of the parameters in response to changes in the conditions described by the models. Since each numeric can be assigned a cost figure, changes in the conditions can be converted directly to cost changes. Thus, practical cost-reliability tradeoffs are now possible on a routine computational basis. These may be based on preliminary estimates of probable numerics or be derived more accurately from subsequent measurement of actual numerics as the program develops and measurement figures become available to replace the a-priori estimates.

C. APPLICABILITY OF MODELS

To better understand how the models relate to one another and how they apply to real world problems, it is helpful to consider the familiar reliability "Bathtub" curve as shown in Figure 17. This curve, plotting failure rate with time, was first derived by Mr. Ryerson in 1954 from actual factory and field

TABLE X. THEORY AND MODEL RELATED RELIABILITY SUBJECTS

A.	Figures of Merit	
	Failure Rate	λ
	Meantime between failures	MTBF
	Meantime to failure	MTTF
	Meantime to lot failure	μA
	Probability of Survival	Ps
	Probability of Failure	P_f
	Cumulative Failure Distribution	F(t)
	Failure Hazard	Z
	Detection Efficiency	D
	Percent Reliability Defective	q
	Percent Quality Defective	Q
	Distribution Shaping Parameter	β
	Quantity of Failures	n_t
	Quantity of repetitive stresses	ψ
	Hours between measurements	h
	Inspector Judgment	J
	Worker generated Defects	G_w
	Process generated Defects	G_p
	Interval Yield	
	Potential Yield	$\overset{P}{Y}$
	Apparent Yield	$\overset{A}{Y}$
	Real Yield	$\overset{R}{Y}$
B.	Burn-in (Part, Unit, System, etc.)	
C.	Conditioning (powered and unpowered)	
D.	Infant Mortality (needed time and stress impact)	
E.	Normal (Poisson) Operating Period	
F.	Longevity and Wearout	
G.	Degrading Stresses	
H.	Reliability Screening	
I.	Reliability Growth	
J.	Risk and Confidence	
K.	Reliability Testing	
	Qualification	
	Acceptance	
	Screening	
	AGREE	
	Validating	
	Repeat Verification	
L.	Rework Costs	
M.	Total Life Costs	
N.	Test Cases	
O.	Storage Cases	
P.	Control Effectiveness	

C.2

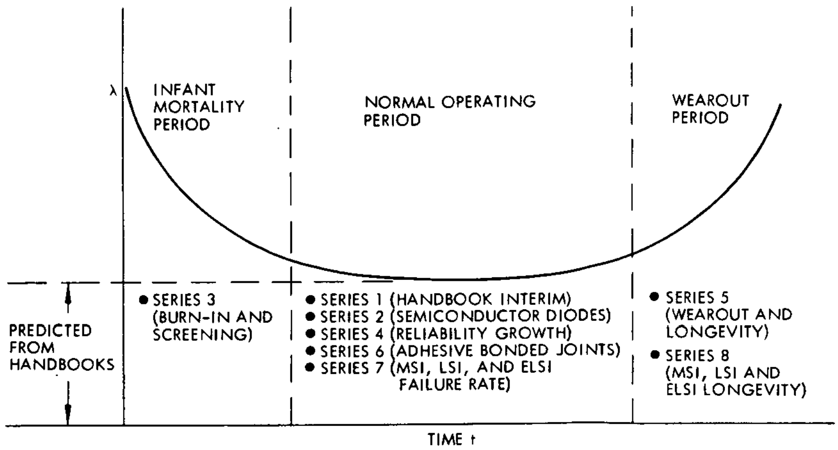


Figure 17. Model Correlation to the Reliability "Bathtub" Response Curve

data to show the three different periods in an operating life cycle. The central or NORMAL OPERATING PERIOD (Figure 17) is characterized as having a constant or nearly constant failure rate. It is the height of this portion of the failure rate curve which is predicted from reliability handbooks such as the RADC Reliability Notebook or MIL-HDBK-217 using Hughes Series 1 (Interim) models. The same failure rate can be predicted more accurately for semiconductor diodes by considering actual stresses and without the need for adjustment K factors by using the basic models of Series 2. When other series of models of the basic type are developed for all the part types, an entirely different handbook presentation will be possible.

The modeling attention next shifted to the general conditions of screening and burn-in associated with the INFANT MORTALITY PERIOD. This period generally has a decreasing failure rate before the time that equipment and parts have stabilized and failure rates leveled off. The Series 3 models were developed to relate many newly defined key factors in screening and burn-in that apply equally well to parts or systems.

The next Series 4 models defined conditions and response related to Reliability Growth during repeated production. This Series 4 applies at the NORMAL OPERATING PERIOD of Figure 17 for subsequent equipments of a given type but relate to the change of failure rate (or its reciprocal the MTBF) with calendar time after initial production and the unit of production.

The Series 5 models on wearout and longevity apply particularly to the WEAROUT PERIOD of Figure 1 for equipments and systems. They also apply during the NORMAL OPERATING PERIOD to mechanical and electro-mechanical devices that normally operate with a wearout characteristic. Indeed for complex systems involving wearout type items, the Series 5 models are key to the time of termination for the normal operating period. When the potential failure hazard for low population short life items reaches a critical value, it exceeds the normal level of random or decreasing failure rate and defines the beginning of the system wearout curve. This longevity or time to wearout is an important factor in successful preventive maintenance.

The Series 6 models on adhesive bonded joints have certain similarities to the Series 5 models but relate to the fatigue strength or wearout of complex adhesive bonded structures under repetitive stresses. For mechanical adhesive bonded structures, these Series 6 models predict conditions and time to malfunction or failure rate in time under cyclic stresses. Thus for these structures, the Series 6 models apply to the normal operating period.

In this same frame of reference, the Series 7 models will apply to the constant failure rate portion in the life of LSI and MSI microcircuits similar to the coverage of the Series 2 basic models for semiconductor diodes. The Series 8 models will describe longevity and long life characteristics of MSI and LSI similar to the coverage of the Series 5 models for mechanical and electro-mechanical devices. These last two model series will be most helpful for designing reliable long-life unattended spacecraft. It is believed that with only minor modification, if any, these same models Series 7 and 8 will apply with equal accuracy to the new extra large scale integrated circuits ELSI. Note that normal wearout of microcircuits occurs so long delayed in time as to be a negligible consideration. This is not true, however, when high energy radiation fields are present. Under these stress conditions, all semi-conductor devices exhibit a degradation with time that has wearout characteristics.

It is impossible to illustrate and explain all these models in this report but a few examples are given in the next section.

D. MODEL APPLICATION EXAMPLES

Example 1.

Given the Model:

$$q_{o_i} = \frac{1 - P_s}{N\ D_i\left(1 - \frac{1}{F_s}\right)} \tag{1}$$

This model is useful to the contractor for interpreting the P_s (probability of survival) requirement imposed by his contract. This requirement might state that the product must demonstrate an 80-percent probability of survival during a specified AGREE or MIL-STD-781 demonstration test. Suppose the equipment in question has a complexity factor N = 2000 parts and suppose also from a study of the type of equipment and measurements planned for the demonstration test, the detection efficiency is estimated to be a typical value of D_i = 75 percent. The remaining unknowns in the above given model are the values of F_s that are the screening strength total inherent in the manufacturing operation and q_{o_i} which is the fraction reliability defective required of the equipment at the start of the test interval if the demonstrated probability of survival is to meet the 75 percent requirement.

To find the value of F_s for the given acceptance test, another model must be used. To simplify this example, it is assumed that the environmental and load stress profile of the demonstration test is analyzed and found to have a typical (moderate) value of F_s = 2.5. By substituting these values into the given model the value of q_{o_i}, which is the factory goal, can be computed:

$$q_{o_i} = \frac{1 - P_s}{N\ D_i\left(1 - \frac{1}{F_s}\right)} = \frac{1 - 0.8}{(2,000)(0.75)\left(1 - \frac{1}{2.5}\right)}$$

$$= \frac{0.2}{900} = 0.00022 \text{ or } 0.022 \text{ percent}$$

This computation says that if the equipment is to pass the specified test with the specified probability of survival it must contain no more than 0.022 percent reliability defectives at the end of the manufacturing operation and just before entering the demonstration test. Another simple model gives a further interpretation:

$$F_m = \frac{q_o}{q_t} \tag{2}$$

This model states that the screening strength needed during manufacturing F_m (if the detection efficiency is 100 percent) is equal to the ratio between the incoming fraction reliability defective and the final required outgoing fraction reliability defective. Since the outgoing q_t is the same as the incoming q_{o_i} of the following demonstration test, then this second model becomes:

$$F_m = \frac{q_o}{q_{o_i}} = \frac{q_o \ (\%)}{0.022 \ (\%)} \tag{3}$$

By experience with other programs it is known that if parts are procured to good specifications with screening requirements similar to level B of MIL-STD-883, an average incoming level to manufacturing can be $q_o = 1.0$ percent.

Thus the screening strength required during the manufacturing cycle can be computed:

$$F_m = \frac{1\%}{0.022\%} = 45 \tag{4}$$

Now it is also known that the typical manufacturing cycle has an inherent F_s of less than 10. Thus if special measures are not taken during manufacturing to increase the inherent F_s, there will be no chance of passing the required demonstration test. The exact probability of survival if no special measures are taken and the actual factory screening strength is assumed to be $F_m = 10$ can be computed from the given models as follows:

$$F_m = \frac{q_o}{q_t}$$

$$q_t = \frac{q_o}{F_m} = q_{o_i} \tag{5}$$

$$q_{o_i} = \frac{1\%}{10} = 0.1\%$$

and by rearranging equation (1):

$$P_s = 1 - N D_i \, q_{o_i} \left(1 - \frac{1}{F_s}\right) \tag{6}$$

and substituting the known values for the demonstration test:

$$P_s = 1 - (2000)(0.75)(0.001) \left(1 - \frac{1}{2.5}\right) = 1 - 0.9 = 10\%$$

In other words in the given example where the required probability of survival is 80 percent, the contractor must take special screening precautions if his probability of survival in the specified demonstration is to be higher than 10 percent.

The question is what measures can he take to upgrade his operation so that his product can pass the required demonstration test. Note that the F_m factors in his plant are multipliers. Thus if he introduces additional screening tests at any stage of his manufacturing with time-stress severity of F_f, he can raise the assumed F_m value to the required $F_m = 45$ as follows:

$$F_f = \frac{\text{Required } F_m}{\text{Assumed } F_m} = \frac{45}{10} = 4.5 \tag{7}$$

Such a screening test is not difficult to provide and may consist of only temperature cycling if the predominant failure modes constituting his incoming average $q_o = 1.0$ percent are not current and voltage sensitive.

Example 2

Given the previous example which requires a contractor to apply special screening tests having an effective $F_s = 4.5$, determine the optimum cost-effective point in his operation for this screening.

Assume for this computation that it costs a manufacturer \$10 to replace a failed part at the assembled card level and \$500 to replace the same part if it fails at the system test level. The problem then is one of computing the quantity of failures that will occur per each system-quantity of parts during the special screening tests. Again for simplification assume that detection efficiency D = 100 percent and the problem can be solved using other simple models as follows.

The quantity of failure occurring during a screening test in M_f is

$$M_f = (\text{Fraction Defective Failing}) \times (\text{Total Quantity})$$

$$M_f = \left(q_{o_s} - q_{t_s}\right) N \tag{8}$$

The cost of screening is thus the cost of replacing each part times the number of parts failing during the screening test. If the screening test is applied at the system level where the cost of replacement is \$500 per failure the total cost of screening per system is

$$\text{Total Screening Cost} = (\$/_t) \times \left(q_{o_s} - q_{t_s}\right) \times N$$

$$\text{Costs} = (500)(0.001 - 0.00022)(2000) = \$780/\text{system}$$

At the early assembly or card conditioning level the cost of screening per system is

$$\text{Cost}_{c_c} = (10)(0.01 - 0.0022)(2000) = \$156/\text{system}$$

Many factors affect this final figure, but each factor can be assessed independently and solved in a manner similar to that shown in Table XI

Note that many simplifying assumptions were made in these examples to illustrate the approach. In an actual case more complex models account for such factors as detection efficiency, worker effectiveness, and process efficiency not being 100 percent. These and other factors are explained easily in the available models.

CASE A INCOMING PARTS	NORMAL MANUFACTURE ONLY		DEMONSTRATION TEST
q_o 0.01	F_m 10 $q_t = \frac{q_o}{F_m} = 0.001$ q_{o_i}		$P_s = 10\%$
CASE B	NORMAL MANUFACTURE	SYSTEM TEST SCREENING	
$q_o = 0.01$	$F_m = 10$ $q_{t_m} = \frac{0.01}{10} = 0.001$	$F_{s_s} = 4.5$ $q_{t_s} = \frac{0.001}{4.5} = 0.00022$	$P_s = 80\%$
COST OF SCREENING = (500) (0.001 - 0.00022) (2,000) = \$780/SYSTEM			
CASE C	CARD CONDITIONING SCREENING	NORMAL MANUFACTURE	
$q_o = 0.01$	$F_{c_s} = 4.5$ $q_{t_c} = \frac{0.01}{4.5} = 0.0022$	$F_m = 10$ $q_{t_m} = \frac{0.0022}{10} = 0.00022$	P_s 80%
COST OF SCREENING = (10) (0.01 - 0.0022) (2,000) = \$156/SYSTEM			

Figure 18. Cost Tradeoff Comparison

E. PROGRAM CONTROL USING THE MODELS

It may not be obvious from the previous discussion how the new models constitute powerful tools for system program control and cost tradeoff. It is important to recognize that all the parameters are defined so that they can be quantified using actual design, factory, field, and related statistics. Detailed cost data are included so that every step of computation, representing a finite step in a program, can be cost analyzed. Thus, any phase or step of a program can be represented either with assumed or actual data to make effective cost tradeoffs and to plan economic program controls for optimized expenditures. Also at each computation point the reliability impact is easily derived for both the immediate set of conditions and conditions likely to exist further downstream in the product life cycle. Thus the models provide direct correlation between plans, actual circumstances, and probable future occurrences for both cost and reliability.

In brief, the models represent a practical bridge between the specialty fields of product effectiveness, value engineering, quality assurance, and reliability. It might be obvious also that the implementation of the models could be described truthfully as advanced production engineering.

An immediate benefit of this modeling approach is the clarification it provides concerning the areas of program and factory control that should be documented more accurately and what specific data should be correlated and analyzed. Means are established for achieving optimized factory cost tradeoffs with specific control measures based on actual data from each process step. Finally the models provide procedures and guides for making better use of presently existing manufacturing data and its related processing and interpretation methods and instrumentation.

Specific applications of the modeling method can be related to different phases of a program life cycle as follows:

1. Early in the system planning, accurate definition of the key or critical program parameters provides guidance to preliminary planning and reveals the emphasis and priority needed on various controls to achieve a specified result.

2. Using an approximate set of assumed parameter values, early program plans can include a preliminary set of cost allocations and standards that should achieve a specified system reliability at a known minimum cost.
3. The impact of any potential set of program changes can be estimated accurately in advance to provide optimum direction to program controls and to establish program priorities.
4. As the program progresses, the preliminary assumed data can be replaced in the models with actual measured facts. The impact of any serious descrepancies between the original assumed and the actual data can be re-evaluated frequently to provide guidance for any necessary changes in program controls or objectives.
5. As the program progresses, the effectiveness and results from the controls and actions can be used to assess the need for improvements in the methods of planning and preliminary estimating.
6. From the start of the modeling effort on any program, benefits will arise from establishing numerical ratings for factors now controlled only intuitively or not at all.
7. During design stages, details of optimum manufacturing controls can be worked out from the models and specific methods devised for integrating with supplier and subcontractor control programs.
8. During the manufacturing phases the effects of program controls can be evaluated and reflected in process and other program changes and in improved methods for corrective action, data handling, rating of workmanship, understanding process limitations, and in improving quality control methods, inspection efficiency, and in reducing defect escapes during acceptance.
9. As completed assemblies and systems are tested and evaluated, the program predictions can be updated for the impact on final product achievement in Demonstration, Service Test, and Field Use. Also final adjustments to the modeling parameters can be made for use in subsequent applications and other programs.

10. The usual system program life cycle is a true stochastic series. Thus, the conditions and facts that exist at any step or interval during the life cycle are directly dependent on the events and conditions that transpired previously. Without well planned and executed program controls, the reliability and cost progress during the life cycle are also stochastic in the sense of random progress. Thus it is fruitless to even consider realistic cost tradeoffs and optimum cost of high reliability on the typical system program. The advantage of the control approach described herein is that the modeling tools have the power of freezing the random character of the stochastic events. If program controls are exercised according to parameters in the models, the life cycle events become deterministic and obey the "laws" of the models.

The implications that result are summarized below:

1. The models enable the program manager and his assistants to determine what factors should be controlled and how.
2. The deterministic models reveal what starting points and operating policies must be established. These are based on an exercise starting with the required final reliability and cost result that must be achieved on a program and a knowledge of what has been or can be controlled in a contractor's operation.
3. Intermediate milestones and related program status can be defined from the models based on the computed starting points and operating policies.
4. The planned program controls according to the models should result in specific achievements of cost, reliability, and program progress trends at precomputed milestones.
5. Actual measurement of cumulative cost, reliability, status, and progress trends at any milestone will confirm the status as originally predicted for that step if the program controls truly complied with the conditions originally assumed for the models.

6. If the measured status at any milestone does not conform to the predicted status, a flag is raised for program management. Specific corrective action steps are possible and can again be optimized by utilizing other models.
7. An analysis of the reasons why the measured status does not conform to the predicted will reveal one or more of the following causes which then can be corrected by suitable management action:
   a. The program controls exercised did not follow the conditions assumed for the model at the time of the original prediction. Increased effort or "patch-up" efforts are indicated.
   b. Some of the parameter values assumed were erroneous or were not constant up to the time of the divergent milestone. The optimum corrective action here may include changing the parameter values or changing the controls so that subsequent predictions and related actual measurements will converge with the determined optimum status.
   c. Defective lots of parts or subcontract supplies did not comply with the expected status. Direct action with the suppliers is indicated in this case.
   d. Workmanship and process efficiency or inspection effectiveness did not measure up to the expected values. The specific steps involved in the optimum corrective action include training the operators and inspectors, improving process control, increasing the strength or length of screening tests, etc., according to the results from a direct investigation of the causes and seriousness of the deviation from the predicted status.
8. In addition to providing for suitable corrective program action, the flag raised called for an investigation to enable management to assess program priorities and the seriousness of program deviation from the predicted. In some cases, serious trouble at a later step can be prevented by keeping the customer and other interested parties advised of current difficulties. Therefore, it can be seen that the time-span between prediction milestones should not be long to enable detection of early deviation trends before they become large.

V. RECOMMENDATIONS

This study has determined the feasibility of developing and verifying the validity of "basic" type prediction models for use with LSI microcircuits. It is recommended that this work be accomplished in three steps as follows:

1. Model Development

   a. Define specific modeling guides, postulates and first and second order simplifying assumptions needed for making the models practical and easy to use.

   b. Define the basic "family modes" which must be represented in the model to describe true-life degradation conditions.

   c. Estimate the probable ranges and limits for each of the major factors and model terms.

   d. Develop mathematical relations suitable for use as terms in the model based on the conditions and assumptions for each of the key factors and inter-action effects. These shall incorporate all the phenomena and failure mode and mechanism effects revealed by this feasibility study.

   e. Generate preliminary general equations relating all the key factors.

   f. Exercise the general equations to demonstrate their practical use in hypothetical cases by using typical data as developed during this feasibility study.

2. Model Validation

   a. Expand the preliminary general equations into detailed variant models for specific applications and conditions.

b. Design and perform test experiments and data research needed to establish the numerical values of the model parameters for specific devices and conditions.

c. Select a restricted typical generic family of microcircuit as used in a realistic application for illustration purposes. This could be a common type of Hybrid LSI as used in an airborne environment.

d. Demonstrate a practical application of the variant models for the selected device using input data as summarized during the feasibility study.

e. Design a practical test experiment to verify the assigned parameter values or to provide input information for necessary corrections to the models. This experiment plan shall include a detailed test specification with tentative contents as follows:

   (1) Design of part type to be tested

   (2) Test conditions and duration

   (3) Quantities of samples involved

   (4) Instrumentation requirements

   (5) Data Requirements

      - Data to be recorded
      - Methods of recording, handling, analyzing etc.
      - Interpretation and reporting

   (6) Failure modes to be expected

   (7) Types and quantities of failures expected (based on exercise of the models)

   (8) Discussion of expected results

3. Model Verification

This project phase will involve an extensive program of test verification according to the test specification developed during the validation phase. A suitable quantity of test specimens will be manufactured and tested to establish statistical confidence in the accuracy of the prediction models and methods.

APPENDIX A

DERIVATION OF THE SCREENING STRENGTH MODEL (F_s)

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Starting with a consideration of the number of failures to be expected during an interval of time involving some combination of environmental and loading stresses:

Number of failures f_i = Fraction Detected x N or

$$f_i = \overset{r}{q}_i N \tag{1}$$

But

$$\overset{r}{q}_i = \left(q_o - \overset{D=1}{q_t}\right) D_i \tag{2}$$

Therefore

$$f_i = \left(q_o - \overset{D=1}{q_t}\right) D_i N \tag{3}$$

But

$$\overset{D=1}{q_i} = \frac{q_o}{F_i} \tag{4}$$

So

$$f_i = q_o D_i N \left(1 - \frac{1}{F_i}\right) \tag{5}$$

Solving for F_i

$$F_i = \frac{1}{1 - \frac{f_i}{q_o D_i N}} \tag{6}$$

Now define the number of failures as,

$$f_i = D_i N q_o P_f \quad (7)$$

Where:

$N q_o$ is the total potential number of failures

D_i is the detection efficiency during the interval

P_f is the failure probability

Substituting (7) into (6)

$$F_i = \frac{1}{1 - P_f} \quad (8)$$

or

$$F_i = \frac{1}{P_s} \quad (9)$$

Also by rearranging (7)

$$P_f = \frac{f_i}{D_i N q_o} \quad (10)$$

and

$$P_s = 1 - \frac{f_i}{D_i N q_o} \quad (11)$$

Where P_s is the success probability

From a study of the various environmental (not loading) stresses which can contribute to screening, the three major are:

1. Temperature T (in ^{o}C)
2. Temperature Cycling dT/dt (Time rate of change of temperature in ^{o}C per minute)
3. Vibration (in g's rms)

The probability of failure due to these three stresses acting either separately or in combination is given by:

$$P_f = 1 - \left(1 - P_{f_T}\right)\left(1 - P_{f_{dT}}\right)\left(1 - P_{f_v}\right) \qquad (12)$$

Where:

P_{f_T} is the probability of failure due to temperature

$P_{f_{dT}}$ is the probability of failure to time-rate-of-change of temperature

P_{f_v} is the probability of failure due to vibration

But Equation (12) reduces to:

$$P_f = 1 - P_{s_T} P_{s_{DT}} P_{s_v} \qquad (13)$$

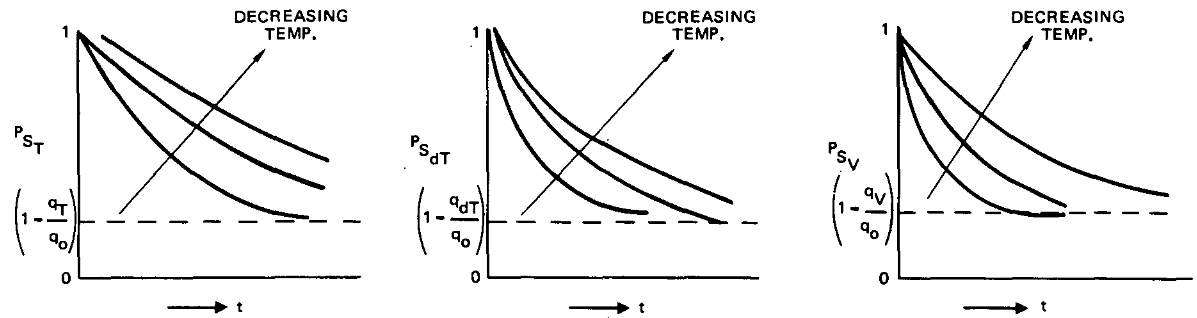
Thus the probability of survival becomes:

$$P_s = 1 - P_f = P_{s_T} P_{s_{DT}} P_{s_v} \qquad (14)$$

and equation (9) becomes:

$$F_i = \frac{1}{P_{s_T} P_{s_{dT}} P_{s_v}} \qquad (15)$$

The individual survival probability functions are illustrated as:



Where each function approaches assymtotically to the lower limit which is determined by the fraction of the total q_o that is screenable by the particular stress involved.

The functions are

$$P_{s_T} = \left[\frac{q_T}{q_o} e^{-\psi s_T \left(\sum_i t_i e^{-\frac{A}{T_i+273}}\right)} + \left(1 - \frac{q_T}{q_o}\right)\right] \tag{16}$$

$$P_{s_{dT}} = \left[\frac{q_{dT}}{q_o} e^{-\psi \sum_i \left(S_T + S_{dT_i}\right) t_{dT_i} e^{-\frac{A}{TE_{dT}+273}}} + \left(1 - \frac{q_{dT}}{q_o}\right)\right] \tag{17}$$

$$P_{s_v} = \left[\frac{q_v}{q_o} e^{-\psi \sum_i (S_T + S_v) t_{v_i} e^{-\frac{A}{TE_v+273}}} + \left(1 - \frac{q_v}{q_o}\right)\right] \tag{18}$$

or:

$$P_{s_T} = 1 - \frac{q_T}{q_o}\left[1 - e^{-\psi S_T \sum_i t_s e^{-\frac{A}{T_s+273}}}\right] \tag{19}$$

$$P_{s_{dT}} = 1 - \frac{q_{dT}}{q_o}\left[1 - e^{-\psi \sum_i \left(S_T + S_{dT_i}\right) t_{dT_i} e^{-\frac{A}{TE_{dT}+273}}}\right] \tag{20}$$

$$P_{s_v} = 1 - \frac{q_v}{q_o}\left[1 - e^{-\psi \sum_i \left(S_T + S_v\right) t_{v_i} e^{-\frac{A}{TE_v+273}}}\right] \tag{21}$$

Thus substituting in Equation (15) gives the effective Screening Strength F_i for an interval i:

$$F_i = \frac{1}{\left\{1 - \frac{q_T}{q_o}\left[1 - e^{-\psi S_{T_i} \sum_i t_i e^{-\frac{A}{T_{op}+273}}}\right]\right\}\left\{1 - \frac{q_{dT}}{q_o}\left[1 - e^{-\psi \sum_i (S_T+S_{dT}) t_{dT} e^{-\frac{A}{TE_{dT}+273}}}\right]\right\}\left\{1 - \frac{q_v}{q_o}\left[1 - e^{-\psi \sum_i (S_T+S_v) t_{v_i} e^{-\frac{A}{TE_v+273}}}\right]\right\}} \tag{22}$$

Where for the case of monolithic microcircuits:

$$T_{E_i} = T_{op_i} \quad \text{in } ^oC \tag{23}$$

$$T_{E_{dT_i}} = \frac{\left|T_{U_i} - 25\right| + \left|T_L - 25\right| + 50}{2} \quad \text{in } ^oC \tag{24}$$

$$T_{E_{V_i}} = \left|T_{op} - 25\right| + 25 \quad \text{in } ^oC \tag{25}$$

$$S_T = 2.0 \quad \text{(for monolithic IC's)} \tag{26}$$

$$S_{dT_i} = (1.0 \text{ to } 4.5) \times \frac{dT}{dt}_{(\text{in } ^{o}C/\text{min})} \tag{27}$$

$$S_{V_i} = (1.0 \text{ to } 3.0) \times g's_{rms_i} \tag{28}$$

$$A = 2298 \text{ (for monolithic IC's)} \tag{29}$$

APPENDIX B

THE HUGHES INTERIM HYBRID RELIABILITY PREDICTION TECHNIQUE

(From HAC Designers Reliability Handbook R-67-3)

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MICROCIRCUITS, HYBRID

Table 61. Prediction Procedure

Part specifications covered

Nonstandard part - no military specification presently exists for hybrid microcircuits.

Hybrid Failure Rate Model (λ_H):

$$\lambda_H = \lambda_b \; (\pi_E \times \pi_T \times \pi_Q)$$

where:

π_E = an environmental factor from Table 62.

π_T = a temperature factor from Figure 24. THE STRESS RATIO IS THE ACTUAL DISSIPATION DIVIDED BY THE RATING.

π_Q = a quality factor from Table 63.

λ_b = base failure rate from the following:

Base Failure Rate Model (λ_b)

$$\lambda_b = A_s \lambda_{sub} + A_s \lambda_c + N_{PC} \lambda_{PC} + \lambda_{PF} \pi_{PF} + \Sigma N_{RT} \lambda_{RT} + \Sigma \lambda_{DC} N_{DC} + \Sigma \lambda_{cp} N_{cp}$$

where:

$A_s \lambda_{sub}$ = the hybrid circuit substrate failure rate and is computed as 0.001%/1000 hours times the area of the substrate in square inches. If the actual area of the substrate is unknown, use 50% of the external package area or 0.2" less than dimensions, whichever is greater, to compute the area of the substrate.

$A_s \lambda_c$ = the failure rate contribution due to the network complexity. The values are found in Figure 26 as a function of the number of separate conductive areas (resistors and conductive paths plus the number of interconnect wires) per square inch of substrate. Assume 2 interconnect wires for each transistor chip, one for each diode chip, and one for each external connection for ICs unless details to the contrary are available.

Table 61. Prediction Procedure (continued)

$N_{PC}\ \lambda_{PC}$ = the number of screen and fire cycles required to form the thick film pattern on the substrate or the number of mask-etch cycles required to form the thin film network pattern on the substrate times .0004%/1000 hours which is the failure rate term for each cycle used in manufacturing the hybrid. If number of cycles is unknown, assume 3 cycles.

$\lambda_{PF}\ \pi_{PF}$ = The hybrid microcircuit package failure rate which is a function of the package style or configuration and the materials used in its construction.

where:

λ_{PF} = 0.002%/1000 hours. This is a normalized value of base failure rate for all hybrid microcircuit packages.

π_{PF} is an adjustment factor which modifies λ_{PF} as a function of the package style and the materials used in its construction. The values of π_{PF} are tabulated in Table 65 for various combinations of style and material.

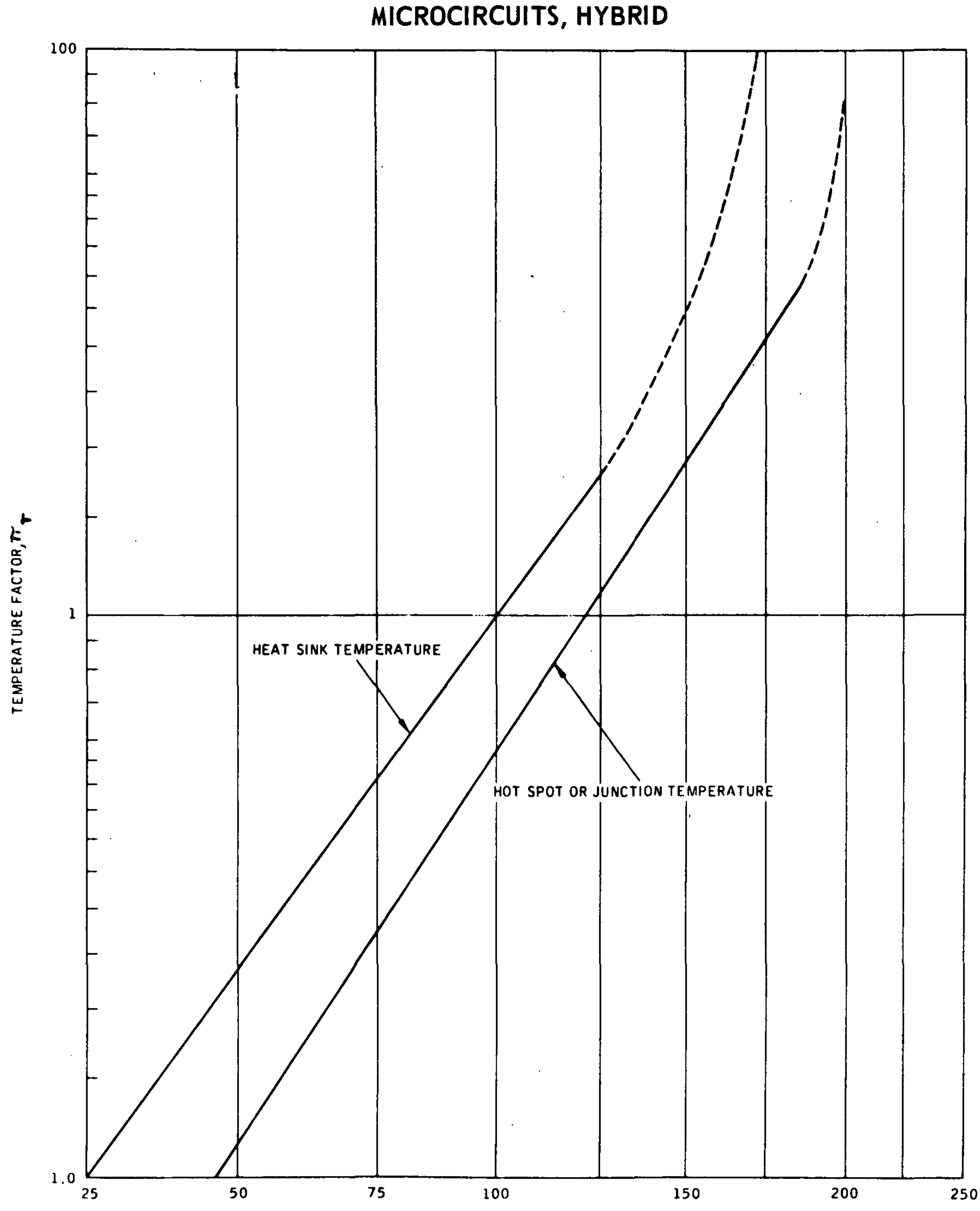
$\Sigma N_{RT}\lambda_{RT}$ = the sum of the additive failure rates for each resistor as a function of the required resistance tolerance.

N_{RT} is the number of film resistors of a given tolerance.

λ_{RT} is the failure rate to be used for each resistor of a given tolerance as specified in Table 66.

$\Sigma\lambda_{DC}\ N_{DC}$ = the sum of the discrete chip device failure rates for semiconductor, IC and capacitor chips. The failure rate is computed as shown in Table 67.

$\Sigma\lambda_{cp}\ N_{cp}$ = the sum of the failure rates of the conventionally packaged devices used in construction of the hybrid microcircuit (glass packaged diodes, molded resistors or capacitors). Until more information is available chip resistors should be treated as their equivalent in leaded discrete devices. The failure rate is obtained by computing the failure rate in the normal manner at 25°C, excluding the environmental factors π_E and Σ_E.



(Heat Sink or Hot-Spot Junction Temperature °C)

Figure 25 π_T - Temperature Factor for Thick Film and Thin Film Hybrid Circuits

Note: The values of π_T obtained from the above curve using heat sink temperature is suitable for hybrid circuits which have less than 20°C temperature rise from heat sink to hot spot or junction. This covers the majority of hybrid circuit designs. Where temperature rise is present due to high chip or total hybrid power dissipation or high thermal resistance from the hybrid to heat sink, a more detailed evaluation is required.

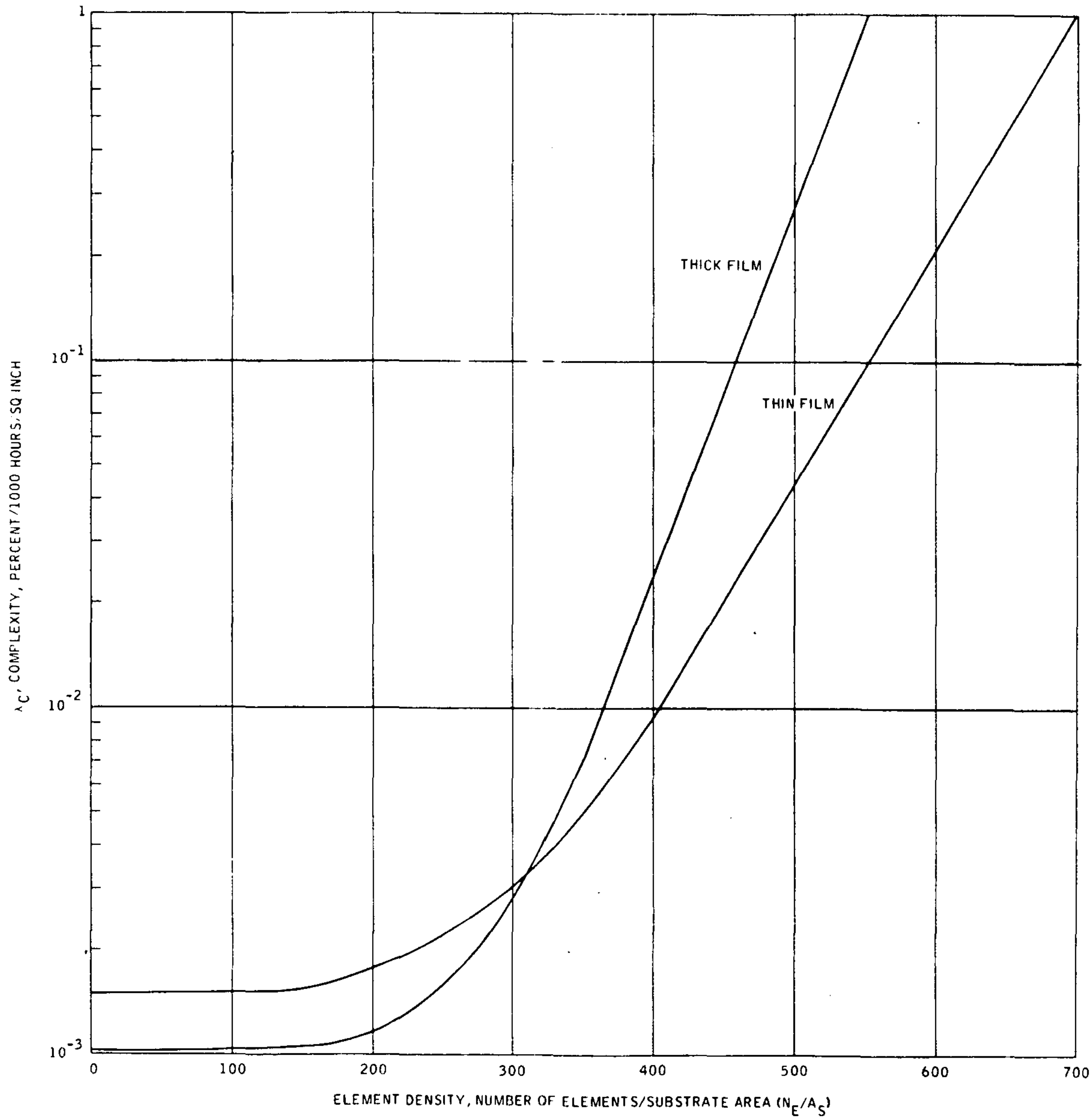


Figure 26 λ_C Complexity Term for Thick, and Thin, Film Hybrid Circuits

Table 62. π_E, Environmental Factor Based on Environmental Service Condition

Environment	Symbol	π_E
Space Flight	S_f	1.5
Ground Fixed	G_f	2.0
Airborne, Inhabited	A_i	5.0
Naval, Sheltered	N_s	6.0
Ground, Mobile	G_m	7.0
Naval, Unsheltered	N_u	7.0
Airborne, Uninhabited	A_u	7.0
Satellite, Launch	S_l	8.0
Missile, Launch	M_l	10.0

Table 63. π_Q, Quality Factor

Specification Control Level	A	B	C	D
π_Q	0.2	0.4	1.0	4.0

Refer to the Detailed Stress Analysis Section for a description of Control Levels. If no level is specified then the π_Q for the C Level must be used.

Table 64. Adjustment Factor, π_{PF}, for Hybrid Microcircuit Package Failure Rate

Type of Package	π_{PF}
Flatpack	
Kovar, Solid	1.5
Other Metal	2.0
Alumina	2.0
Dual Inline	2.5
TO-5	
Kovar Header	1.0
Glass Header	1.2
Axial Lead Packs	
Metal	1.0

Table 65. Failure Rate λ_{RT}, for Hybrid Network Thick and Thin Film Resistors versus Resistor Tolerance

Resistor Tolerance (± Percent)	Resistor Failure Rate λ_{TR} (Percent/1000 hrs)	
	Thin Film Resistors	Thick Film Resistors
0.1 to <1.0	0.000050	---
1.0 to <2.0	0.000025	0.000050
2.0 to <5.0	0.000020	0.000030
5.0 to <10.0	0.000015	0.000020
> 10.0	0.000005	0.000005

Table 66. λ_{DC}, Failure Rate for Discrete Device (Chips) When Used in Hybrid Microcircuits

	λ_{DC} Failure Rate (Percent/1000 hrs)	
Discrete Chip Description	Bonded Wire Lead (Face-Up) Devices	"Flip-Chips", Bumped, Beam, Lead, or Tab Lead Devices
Capacitors		.0005
Diodes		
Si Low-Power Switching	0.00015	0.00020
Si General Purpose	0.00025	0.00030
Si Rectifiers	0.00045	0.00050
Ge Switching	0.00100	0.00100
Ge Rectifiers	0.00200	0.00200
Zener	0.00030	0.00035
Varactor	0.00200	0.00200
Tunnel	0.00200	0.00200
Transistors		
Si Low-Power Switching	0.0003	0.0004
Si General Purpose	0.0005	0.0006
Si Power > 1.0 Watt	0.0033	0.0033
Ge Low-Power Switching	0.0007	0.0008
Ge General Purpose	0.0013	0.0013
Ge Power > 1.0 Watt	0.0050	0.0060
FET	0.0012	0.0015
Unijunction	0.0060	0.0065
Silicon Controlled Rectifiers (SCR)		
Low Power < 1.0 amp	0.001	0.0012
Power ≥ 1.0 amp	0.004	0.0050
Monolithic Integrated Circuits		
The base failure rate of .0012%/1000 hours is multiplied by the complexity factor from Table 67 and 68.		

Table 67. π_C, Complexity Factor for Digital Microcircuit Chips

Logic	Input Description (Per Function)	Complexity Factor π_C
Basic Single Gate	up to 4 inputs	1.0
Buffer	1 input	
Single Gate	4 to 8 inputs	
Dual Gate	up to 4 inputs	
Expander	up to 5 inputs	
NAND/NOR Gate	up to 5 inputs	
AND/OR Gate	up to 5 inputs	
Dual Inverter	any	
Triple Gate	up to 4 inputs	1.5
Exclusive OR Gate	up to 4 inputs	
Triple NAND Gate	up to 3 inputs	
Triple NAND/NOR Gate	up to 3 inputs	
NAND/NOR with Emitter Follower	up to 6 inputs	
Adder	any	
Quad Gate	up to 4 inputs	2.0
Dual Expander	up to 4 inputs	
Dual NAND/NOR Gate	up to 5 inputs	
Quad Inverter Driver	any	
Triple NAND/NOR with Emitter Follower	up to 4 inputs	
Simple Flip-Flop	2 inputs	2.5
Pulse Exclusive-OR	any	
JK Flip-Flop with Preset AND/OR Clear	any	3.0
Dual Exclusive-OR Gate	up to 4 inputs	
One-Shot Multivibrator		
JK/R-S Flip-Flop	any	
Quad NAND/NOR	any	
Dual Simple Flip-Flop	2 inputs	4.0
R-S Flip-Flop/Counter	any	
Ripple Counters	any	
Dual JK Flip-Flop with Preset AND/OR Clear	any	5.0
Shift Register	any	

Table 68. π_C, Complexity Factor for Linear Microcircuit Chips

Characteristic	Complexity Factor π_C
For each simple or basic function	10.0
For open-circuit voltage gains over 60 db of each basic function	$\left(\frac{\text{open-circuit voltage gain in db above 60 db}}{10.0}\right)$
For each extra or special input (such as noninverting, etc.)	2.0
For each extra or special output (such as emitter follower)	2.0
For each other special feature (such as threshold limiting or extreme frequency response)	3.0
Note: Obtain the total π_C for linear microcircuits by adding appropriate factors from this table.	

EXAMPLE: MICROCIRCUITS, HYBRID

EXAMPLE:

Determining the Failure Rate of a Hybrid Microcircuit

Given: A thin film substrate (0.656 sq. in.) containing 2 transistors and 2 diodes (silicon, general purpose, bonded base down), 4 transistors (silicon >1.0 watt) of the flip-chip design, 2 micro-discrete capacitors, 8 resistors with a tolerance of 5 percent and 25 separate conducting paths. It will be packaged in a glass frit flat pack, operating at a temperature of 65°C in a Ground Mobile service environment. Three mask-etch cycles are required to produce the conductive paths and resistor elements. The circuit dissipates 40% of the package rating.

Find: The failure rate of the microcircuit.

Step 1. $A_s \lambda_{sub}$ substrate failure rate from Table 61

$A_s \lambda_{sub}$ = .001 x .656 = .000656 %/1000 hours

Step 2. $A_s \lambda_c$ network complexity factor from Figure 26

element density = 49/.656 = 75 λ_c = .0015

$A_s \lambda_c$ = .656 x .0015 = .000985 %/1000 hours

Step 3. $N_{pc} \lambda_{pc}$, screen/fire, mask/etch failure rate is found in Table 61 and is .0004 x No. of mask/etch cycles

$N_{pc} \lambda_{pc}$ = .0012 %/1000 hours

Step 4. $\lambda_{pF} \pi_{pF}$, package failure rate is found in Table 61 and equals

$\lambda_{pF} \pi_{pF}$ = .002 x 2.0 = .004 %/1000 hours

Step 5. $\Sigma N_{RT} \lambda_{RT}$, Additive resistor failure rates is found in Table 65

$\Sigma N_{RT} \lambda_{RT}$ = 8 x .000015 = .0012 %/1000 hours

Step 6. $\Sigma \lambda_{DC} N_{DC}$, the discrete chip failure rate is found in Table 66

$\Sigma \lambda_{DC} N_{DC}$ = 4 x .0005 + 2 x .0005 + 2 x .00025

= .0132 + .001 + .0005 = .0157 %/1000 hours

EXAMPLE:

Step 7. $\Sigma\lambda_{cp}N_{cp}$ the sum of failure rates for discrete devices would be found in the other sections of this handbook. For this device

$$\Sigma\lambda_{cp}N_{cp} = 0$$

Step 8. λ_b the base failure rate is the sum of the preceding failure rates

λ_b = .00065 + .000985 + .0012 + .003 + .00012 + .0157

= .02265 %/1000 hours

Step 9. The overall failure rate

$\lambda_H = \lambda_b\ (\pi_E \times \pi_T \times \pi_Q)$

π_E from Table 62 = 7.0

π_T from Figure 25 = 2.5

π_Q from Table 63 for C level = 1

λ_H = .02265 (7 x 2.5 x 1) = .396 %/1000 hours

WORKSHEET: MICROCIRCUITS, HYBRID

HYBRID DETAILED FAILURE RATE PREDICTION WORK SHEET

GENERAL EQUATION:

π_E = ____, π_T = ____, π_Q ____

$\lambda_H = \lambda_b (\pi_E \times \pi_T \times \pi_Q)$

$\lambda_b = .001 A_s + A_s \lambda_c + .004 N_{PC} + .002 \pi_{PF} + \Sigma N_{RT}\lambda_{RT} + \Sigma\lambda_{DC}N_{DC} + \Sigma\lambda_{CP}N_{CP}$

Program ____

Part No. ____

Date ____

Prepared by ____

A_s = ____ x ____ =	(1) ____	Number	Density
Thick Film ☐ /Thin Film ☐		Conductors ____	$\frac{(N)}{(A_s)}$ = ____
$.0004 N_{PC} = .0004$ x ____ =	(3) ____	Resistors ____	
		Wires ____	λ_c =
$.002 \pi_{PF} = .002$ x ____ =	(4) ____	Total (N) ____	$A_s\lambda_c$ = ____ (2)

N_{RT}	<1% ____	1-2% ____	2-5% ____	5-10% ____	>10% ____	
λ_{RT}						
$N_{RT}\lambda_{RT}$	____	+ ____	+ ____	+ ____	+ ____	= $\Sigma N_{RT}\lambda_{RT}$ = ____ (5)

$\Sigma\lambda_{DC}N_{DC}$ — Discrete Chips

Type	Qty	λ	$N_{DC}\lambda_{DC}$
Diodes			
____	____	____	____
____	____	____	____
Xistors			
____	____	____	____
____	____	____	____
Capacitors	____	.0005	____
IC's		π_CComplex.	
____	____	____	____
____	____	____	____
		Total $\Sigma\lambda_{DC} N_{DC}$	(6) ____

$\Sigma\lambda_{CP}N_{CP}$ — Conventional Packaged Parts

Type	Qty	λ	$\Sigma\lambda$
Resistors			
____	____	____	____
____	____	____	____
Capacitors			
____	____	____	____
____	____	____	____
Semi-conductors			
____	____	____	____
____	____	____	____
	Total $\Sigma\lambda_{CP}N_{CP}$		(7) ____

SUMMARY

LINE	MATH FACTOR & MODEL	FAILURE RATE
1	Substrate ($.001 A_S$)	____
2	Complexity ($A_S \lambda_C$)	____
3	Process Cycle ($.0004 N_{PC}$)	____
4	Package Factor ($.002 \pi_{PF}$)	____
5	Resistor Tolerance ($\Sigma N_{RT}\lambda_{RT}$)	____
6	Discrete Chips ($\Sigma\lambda_{DC}N_{DC}$)	____
7	Conventional Parts ($\Sigma\lambda_{CP}N_{CP}$)	____
8	Sum (Lines 1 thru 7)	____
9	Environ. Factor π_E	____
10	Temp. Factor π_T	____
11	Quality Factor π_Q	____
12	Product ($\pi_E \times \pi_T \times \pi_Q$) Times (Line 8)	____ %/1000 hr