PREDICTION OF MEAN TIME BETWEEN FAILURES OF ELECTRONIC SUBSYSTEMS FROM COMPONENT FAILURE RATES DETERMINED UNDER VARYING ENVIRONMENTAL CONDITIONS

by

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INTRODUCTION

This report is an evaluation of the feasibility of predicting the reliability of electronic systems through the analysis of failure rates at accelerated environmental conditions. It contains four major sections describing (1) some basic fundamentals of reliability theory, (2) methods of predicting reliability, (3) various types of accelerated testing, and (4) a typical example of predicting the mean time between failures of an airborne electronic system. It is the specific intent of the author to validate procedures for determining the mean time between failures of an electronic system under accelerated thermal stresses, in an effort to predict the mean time between failures of the same system under use conditions. Background information is supplied to acquaint the reader with definitions, distributions and data sources presently being used by various manufacturers and government agencies.

The absolute necessity for reliability in complex military systems has become the most important reason for the multitude of studies about reliability in recent years. The space program with its demand for acceleration has created a need for reliability prediction with a high degree of accuracy. Unreliability and its accompanying cost can best be described by Lt. General Howell M. Estes (9) the Vice-Commander of the Air Force Systems Command.

> Maintenance of military electronics equipment now ranges between 60 and 1,000 times the initial costs. The progress we have made today in system reliability has simply not been adequate. To cite some examples--a failure of a 2 dollar item in the launch of a space system caused the loss of a 2.2 million dollar vehicle. The failure of a 5 dollar thermal shield resulted in a 23 million dollar disaster. A failure of a 25 dollar fuel valve in a ballistic missile brought about a loss of 22 million dollars.

The costs related here pertained to money losses, but in the space race losses must include human lives. The need for improved reliability prediction becomes obvious when constructing a vehicle for a voyage into space lasting several years.

FUNDAMENTALS OF RELIABILITY

Reliability has been defined in many ways, but the most widely used is this, "Inherent reliability is the probability that the equipment will perform its intended function satisfactorily for a specified period of time when used in the manner and for the purpose intended." (10) Satisfactory performance of the system is considered to be operation within specified functional characteristic limits. Also, satisfactory performance is considered synonymous with success or non-failure and unsatisfactory performance constitutes failure.

The relationship between part and system failure is an essential part of reliability prediction and will be looked at briefly here. One of the basic problems in predicting reliability of a system is determining the expected reliabilities of the individual parts--as they are applied in the system. Having a detailed description of how a proposed system will be employed in a typical mission, the logical structura of system operations can be developed. This structure should link together the probabilities of successful operation of all parts into an expression giving such probability measura for the system as a whole. In this process, which is called "constructing a mathematical modal of the system", the effects of interactions of the various parts on each other, may be estimated from the design. The overall system can be divided into sub-systems whose reliability functions are to be statistically independent of each other. These sub-systems can again be divided into assemblies of parts whose individual reliabilities have been determined. From this it is evident that in any study of system reliability it is essential to determine failure characteristics of individual parts.

Failure Characteristics

To examine the manner in which part failure occur, two categories of failures will be discussed. The first of these are performance degradation failures, and the second are random catastrophic failures. An example of the first type would be an electron tube whose transconductance has diminished to the point of failure from a build-up of interface resistance. The second type of failure is exemplified by tubes which have become inoperative because their heaters have opened.

There are two alternatives to the use of analytical techniques in predicting degradation failures. (21) The most popular is to ignore them and assume that they are a negligible portion of total failures. This approach holds credence because many degradation failures can be eliminated as a result of modern conservative design and such practices as:

1. A design review of each circuit to be employed in a new equipment and subsequent improvement of the circuit.

2. Type testing on a professional level aimed at performance improvement as well as equipment certification.

3. Maintenance practices designed to eliminate those parts approaching wear-out before they fail.

The other approach is to assume that in new systems degradation failures will represent the same proportion of total failures as they did in previous systems. Many data sources include degradation failure rates, but if this information is not included adjustments must be considered.

In the area of catastrophic failure analysis, there are two related computational techniques involved which employ the exponential failure law. One method (referred to as "part count") employs parameters which provide part failure rate by component category. This method is based on a complete part count to which a single overall average failure rate is applied. The second computational method has been used effectively by several groups and includes a greater degree of design detail. This method entails the following steps: (21)

1. The identification of each individual part in terms of its family-type, characteristics, controlling specifications, etc.

2. A decision as to applicability of available statistical guides followed by a choice of satisfactory charts and curves or modification factors.

3. A determination of the equivalent sustained (electrical and ambient) stresses applied to each part.

4. Entry into each appropriate figure for determination of the resultant failure rate for each part.

5. Addition of all hazards as effective failure-rate terms to derive a "grand total" failure-rate term for the system.

The process for determining random catastrophic failure rates is based on the premise that like parts have approximately the same reliability in one system as in any other system, if they are subjected to the same stresses. In order to standardize data information and establish a failure rate data exchange program the Bureau of Naval Weapons instigated the FARADA Program. The FARADA Program currently represents the most comprehensive source of failure rate data and has as its objectives the following: (20)

1. To derive coherent basic failure rates that represent the composite experience of the various program participants without losing the identity of the basic input data.

2. To present the failure rate information in a convenient form for use by design engineers.

3. To convey with each data entry the level of confidence the user may validly attach to the given failure rate.

4. To extend the present failure rate information to include all parts for which data are presently available or will be available in the foreseeable future.

5. To expand and update the current information on the effect of environmental stress factors on part and component failure rates.

This final objective on the effect of environmental stresses is probably the most essential item in the prediction of reliability. FARADA has made it a requirement to furnish the exact environmental conditions under which a particular set of failure data was determined in order to correlate results from various sources.

Although some environmental conditions are impossible to completely simulate, reliable predictions necessitate a study of use conditions. Some of the many environmental conditions FARADA has been concerned with are listed here: (20)

1. Percent of Rated--
   Voltage, Frequency, Current, Power

2. Temperature--
   High, Low, Typical

3. Vibration--
   Mechanical--Type and Frequency
   Acoustic--Intensity and Frequency

4. Shock--
   Maximum Intensity, Typical Duration, Frequency of Occurence

5. Pressure--
   Typical, Range

6. Relative Humidity--
   Typical, Range

7. Radiation--
   Total Absorption, Type

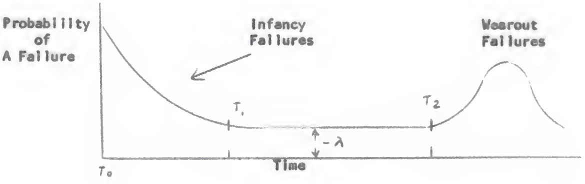
In any complex space electronic system all of the above stresses will be encountered and must be considered when determining failure rates.

Catastrophic failures can be caused by any of the above stress factors, but in most well-designed equipments, the principal factors are electrical and thermal stresses. In the example utilized later in this report only thermal stresses will be considered.

Failures of electronic parts can be more fully understood by considering their failure rate density curves.

Failure Rate Density Curve

The probability - density curve as shown in the following figure consists of three failure stages. (13)



The first of these stages constitutes early failures and begins at time T=0. The population will initially have a high failure rate due to primary material failure or to poor quality control. As these weak components fail, the failure rate decreases fairly rapidly and this is known as the "burn-in" or "debugging" period. This early failure situation is characterized by a conditional failure function which is some form of the negative exponential distribution. Modern engineering techniques require a "debugging" or "burn-in" period before the parts are accepted for equipment assembly. This practice eliminates the substandard components and is essential in the case of missiles, rockets or space vehicles where replacement is difficult after launch. Unfortunately, the cost of complete "debugging" for parts manufacturers is extremely high and there still exists a resistance to requirements demanded by military contractors as evidenced by the following statement of Robert C. Sprague, Chairman of the Board of Sprague Electric Company: (23)

> Consider for example, the problems that will be encountered by the parts manufacturer when 10% to 20% of life test samples must be tested for over 10,000 hours. The management problems associated with test equipment, personnel, and data recording increase many fold over present requirements. For the components supplier, the cost of qualifying his product to one of the several important specifications systems for highly reliable parts has been estimated to run between $250,000 and $500,000 which I think is a conservative estimate.

After time T_2 on the failure probability density curve the period of "wear-out" failures begins. Failures taking place during this period are generally caused by material or dimensional changes due to fatigue, material migration, chemical reactions, and other similar phenomena.

According to Buckland, (6) the failure frequency distribution during wear-out is represented most often by:

1. The Weibull family of distributions.

2. Gamma distribution.

3. Normal or Gaussian distributions.

The chart on tha following page compares thesa distributions.

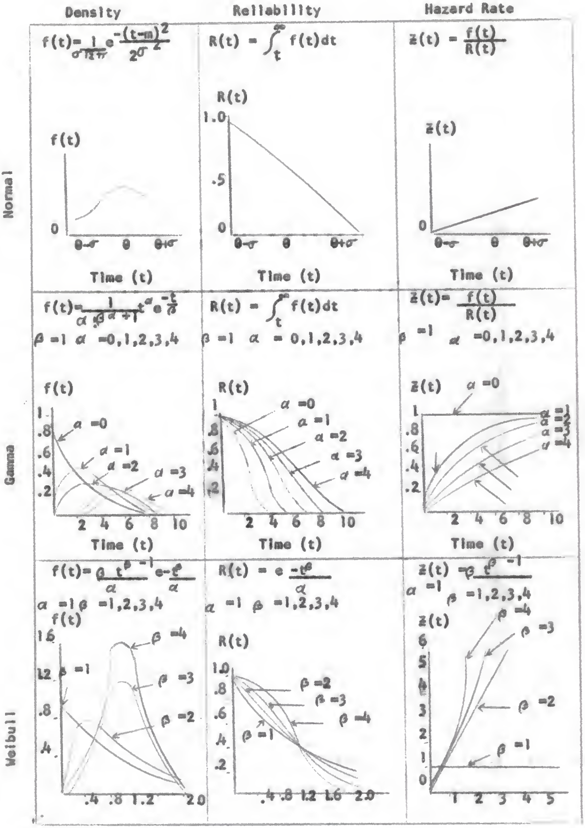
Again accepted raliability concepts require replacement of parts before the wearout period begins. However, if we had a large system with many components in series and chanca failures are absent so that only wearout failures occur, a constant failura rate will evolva and the system will behave exponentially. As a general rula wearout failures must be prevented by early replacement of each part with a part frea of early failures in ordar to attain high system raliability.

The staga of failures from T_1 to T_2 will be tha primary area of consideration in this report and is generally assumed to reprasent the lifa of tha part. To bettar understand this stage of the curva, raliability functions and failure patterns will ba discussed.

A raliability function is defined as a mathematical formula ralating tha probability that the system will operate satisfactorily with a specific period of tima. The natura of this relationship is dependent on the distribution of times to failura of a particular part and theoretically could be of any form. However, most sources agrea that failure patterns can ba represented by a ralatively small number of distribution types. The typas most commonly encountered are (1) the normal or Gaussian, and (2) the exponential which is a special casa of (3) the Waibull. (26) p. 137.

The exponential distribution will ba utilized in the exampla in this report as it is in general acceptanca as indicated in the AGREE Report:

FUNCTIONS


Density
Reliability
Hazard Rate
TYPES
Normal
$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-m)^2}{2\sigma^2}}$
$R(t) = \int_t^\infty f(t)dt$
$z(t) = \frac{f(t)}{R(t)}$
f(t)
R(t)
z(t)
1.0
.5
0
θ-σ θ θ+σ
Time (t)
Gamma
$f(t) = \frac{1}{\alpha!\beta^{\alpha+1}} t^{\alpha} e^{-\frac{t}{\beta}}$
$\beta = 1$ $\alpha = 0,1,2,3,4$
$R(t) = \int_t^\infty f(t)dt$
$\beta = 1$ $\alpha = 0,1,2,3,4$
$z(t) = \frac{f(t)}{R(t)}$
$\beta = 1$ $\alpha = 0,1,2,3,4$
α =0
α =1
α =2
α =3
α =4
1
.8
.6
.4
.2
2 4 6 8 10
Time (t)
Weibull
$f(t) = \frac{\beta t^{\beta-1}}{\alpha} e^{-\frac{t^{\beta}}{\alpha}}$
$\alpha = 1$ $\beta = 1,2,3,4$
$R(t) = e^{\frac{-t^{\beta}}{\alpha}}$
$\alpha = 1$ $\beta = 1,2,3,4$
$z(t) = \frac{\beta t^{\beta-1}}{\alpha}$
$\alpha = 1$ $\beta = 1,2,3,4$
β =1
β =2
β =3
β =4
1.6
1.2
.8
.4
.4 .8 1.2 1.6 2.0
0 1 2 3 4 5 6
1 2 3 4 5

"Field measurements of military and commercial electronic systems have demonstrated that in general the rate of system failure is fairly constant throughout the life of the system."

This means that the observation of a large population of systems has shown that any system chosen at random can be expected to operate satisfactorily approximately the same length of time after being repaired as it operated before failing. The AGREE Report also defines the life of a system as the period during which it fails at a constant rate. If systems in general fail at a constant rate then the probability density function (or failure frequency function) which accurately describes a system's performance is the negative exponential. (1), p. 79.

$$f\ (t) = \lambda \exp\ (-\lambda t)$$

The failure distribution function resulting from f (t) is:

$$F\ (t) = \int_0^t f\ (t)dt = 1-\exp\ (-\lambda t)$$

consequently, the reliability function is:

$$R\ (t) = \int_T^\infty f\ (t)dt = \exp\ (-\lambda t)$$

The exponential density function like other statistical density functions has a characteristic value called the mean. This is obtained for all distributions by forming what is called the first moment $t \cdot f(t)$ of the density function and integrating over the range of f(t). This operation on the exponential density function determines the mean of the function or the mean time between failures.

$$\theta = \int_0^\infty tf\ (t)dt = \int_0^\infty t\lambda \exp\ (-\lambda t)dt = \frac{1}{\lambda}$$

Thus, in the exponential case, the mean time between failures is equal to the reciprocal value of the failure rate λ. Other, nonexponential density functions also have mean time between failures, but they are not the reciprocals of the failure rates.

The density function can be used to determine an important measure of the performance of an equipment called the mean-time-between-failure (MTBF). Since MTBF is an area of primary concern in reliability prediction its derivation and usage will be considered here.

Determination of MTBF

There is no statistical relationship between the MTBF and life of an equipment or part. Many parts have become so reliable that they may be considered to have an infinite MTBF and yet a comparatively short life. Others can be considered to have an infinite life and a comparatively short MTBF. This MTBF can be determined for a system in either of the following two ways. (13)

Method 1

A calculation is performed, based on the summation of the predicted part failure rates. If the individual part failure rates are expressed in percent per 1,000 hours and are signified by $\lambda_1, \lambda_2, \lambda_3, \ldots \lambda_m$, then θ the MTBF is determined as follows:

$$\theta = \frac{10^5}{\lambda_1 + \lambda_2 + \lambda_3 \cdot \cdot \cdot \lambda_m}$$

Method 2

Observations are made of the systems performance during actual operation either in the field or with tests that simulate actual field conditions, and

$$\hat{\theta} = \frac{\sum_{i=1}^{n} Ti + \sum_{j=1}^{m} Tj}{f}$$

where θ is the best estimator of MTBF, Ti is the time duration in hours of the ith observation of n total observations each of which terminated with a failure. Tj is the time duration in hours of the jth observation of m total observations each of which terminated prior to the occurence of a failure, and f is the total number of failures. An example of this method is shown below: (13)

UNIT	HOURS OF FAILURE Ti	NUMBER OF FAILURES f	HOURS NOT ENDING IN FAILURE Tj
1	25	1	75
2	60	1	40
3	15	1	--
	75	1	10
4	None	0	100
5	80	1	20
TOTALS	255	5	245

$$\text{MTBF:} \quad \theta = \frac{255 + 245}{5} = 100 \text{ hours}$$

Only the first of these two methods can be used to predict the reliability of a system before the module is actually constructed. In order to utilize this first method, failure rates of component parts must be determined either from testing or from appropriate tables. With the number of hours an equipment is expect to operate between failures becoming increasingly large, it will be necessary to determine MTBF in terms of days and years rather than hours. For the space program to be effective, it is essential to be able to predict MTBF or the reliability of a system without relying on life testing.

RELIABILITY PREDICTION

Reliability prediction is a method of forecasting the probable reliability of a device by means of past experience or statistical methods. The primary reason for predicting reliability is to determine whether the design of a system is sufficiently mature to ensure mission success. However, because of economical reasons, it is essential to work toward an optimum reliability. The old concept of putting a system into operation in order to test its reliability becomes economically prohibitive with the complexity of today's systems.

In using statistical methods to predict reliability, it must be realized that they are not used to refine proposed designs of unknown quality, but to establish on a probabilistic basis what is known about performance characteristics. A given system's reliability is predictable only in the sense of performance limits within which it will function with a pre-assigned level of probability for doing so. Before selecting a particular method to be used for predicting reliability, an analysis should be made using the following criteria: (12)

1. Project Requirements--Does the project require that a specific technique be employed.

2. Purpose of Prediction--Reliability predictions may be used to establish adequacy of proposed designs, to measure compliance with reliability specifications, and to analyze design improvements. The two require a high degree of accuracy whereas evaluation of alternate designs can utilize a simplified method.

3. The Type of Equipment in a System--Several techniques relating to different types of equipment are available. Switching-circuit analogy, redundancy techniques, and situations where the results of different type failures are important, must be considered.

4. Phase of Design--The phase of the design process determines the amount of detail information available about the equipment.

5. Degree of Accuracy Desired--The refinement of a prediction to include confidence limits associated with estimates and variations in operational requirements necessitates more advanced prediction techniques. As a result of the above analysis it is possible to determine the technique most applicable to meet any requirements.

Some of the techniques available to the engineer are the following:(12)

1. The technique based on the product rule and simple redundancy considerations. This procedure is valid where parts composing a system or sub-systems within an equipment operate in a simple series or redundant configuration.

2. Another approach is prediction by equipment function. This technique involves comparing the system or its parts with that of existing devices with known reliability.

3. A technique useful in the early stages of design of electronic equipment is the active-element-group (AEG) concept. By definition, an (AEG) consists of a tube or a transistor with a proportionate share of the resistors, capacitors, coils, transformers, and other parts which form the module. Failure rate of the new system is predicted by determining the sum of the products of the number of AEG's times their failure rates.

4. A fourth technique sometimes termed "Cause and Effect Analysis", is more qualitative than quantitative. The application of this technique requires a detailed systematic analysis of the relationship of various parts to the whole; identification of modes of failure and the effects of such failures; and analysis of means of eliminating failures.

Regardless of the technique selected, there are certain procedures that should be followed in predicting reliability. The steps listed by ARINC Research Corporation are probably the most comprehensive and will be explained here: (26)

1. Define the System--The task of defining the system consists of describing functions and limits of parts or sub-systems.

2. Define Failure--Normally failure is described as any condition which renders the system incapable of operating within its specified performance parameter limits. Any other concept of failure should be labeled as such.

3. Define Operating and Maintenance Conditions--Operating conditions include the environmental conditions prevailing during various periods of operation. This includes a concept of duty cycles which has become of importance in recent years. There is evidence of a requirement for failure rates during off-duty time as noted in the following quote: (16), p. 86 "The traditional practice of using component part failure rates derived from field data to predict the reliability of future equipments without any regard to duty cycle can result in erroneous predictions." The same results were noted in a study by IBM. The IBM Space Guidance Center had analyzed the reliability of more than 100 transistorized military guidance computers over a period of two years. Analysis of two sub-groups of

computers showed that the sub-group that had experienced 300 percent more "on time" had operated for 170 percent longer time between failures. Maintenance conditions become important for determining replacement schedules and preventive maintenance times.

4. Construct Reliability Block Diagram--Several block diagrams might be required to separate the system in sub-systems or even parts depending on the complexity of the system. Primary consideration should be given to arranging blocks with regard to redundancy, duty cycles, separate failure rates, and parallel or series circuitry. If system operations or environments vary during a particular mission, this must be constructed as a separate block diagram.

5. Develop Reliability Formulas--Some examples of basic formulas for computing reliability are considered here: (1), p. 85-120.

a. If a component has a reliability R_1 and another has a Reliability R_2, then the probability that both will be operating at time (t) is:

$$R_s\ (t) = R_1\ (t) \cdot R_2\ (t)$$

In the exponential case with constant failure rate this becomes:

$$R_s\ (t) = \exp\left[-\int_0^t \lambda_1\ dt\right] \cdot \exp\left[-\int_0^t \lambda_2\ dt\right]$$

or

$$R_s = \exp -\left[\lambda_1 + \lambda_2\right] t$$

For n sub-systems in series with failure rates equal to λ_i the system's reliability becomes:

$$R_s = \exp\ (-\sum_{i=1}^{n} \lambda_i\ t)$$

The probability that either one or both of the components will survive is:

$$R_p(t) = R_1\ (t) + R_2(t) - R_1(t) \cdot R_2(t)$$

and again using the exponential case with constant failure rates the equation becomes:

$$R_p(t) = \exp\left[-\lambda_1 t\right] + \exp\left[-\lambda_2 t\right] - \exp-\left[\lambda_1 + \lambda_2\right]t$$

b. The reliability of n components in parallel is given below with $Q_i(t)$ meaning the unreliability:

$$R_p(t) = 1 - \prod_{i=1}^{n} Q_i(t)$$

If the components in parallel have equal failure rates, which is very often true, the equation simplifies to:

$$R_p(t) = 1 - Q_n = \left[1- \quad 1-\exp(-\lambda t)\right]^n$$

where Q is the unreliability of one component and n = number of components.

c. Another consideration is the reliability of stand-by systems. For a stand-by system of three units with the same failure rate, where one is operating and the other two are standing by, the reliability formula is:

$$R_b = \exp(-\lambda t) \cdot \left(1 + \lambda t + \frac{\lambda^2 t^2}{2!}\right)$$

In general with n equal components standing by the formula is:

$$R_b = \exp(-\lambda t) \cdot \left(1 + \lambda t + \frac{\lambda^2 t^2}{2!} + \cdots + \frac{\lambda^n t^n}{n!}\right)$$

The advantage of stand-by arrangements results not from a significant increase in reliability, but in a considerably longer MTBF. In the formulas above the reliability of switching devices was considered to be 100 percent however, if switches have other than 100 percent reliability they must be included as indicated below with one stand-by system backing up an operating system. R_{ss} = Switching Reliability

$$R_b = \exp(-\lambda t) + R_{ss} \exp(-\lambda t)\lambda t$$

d. A final consideration can be utilized whether or not the components are equal or fail exponentially. This consists of first deriving the density function of systems in stand-by, and then obtaining the cumulative reliability of the system by the integration of the density function.

$$R_b = \int_t^{\infty} f(t)dt$$

e. All of tha above stand-by formulas assume that the stand-by unit does not fail while no. in operation, but as was indicated earlier in this report--off duty time can contribute significantly to failura of an equipment. For this typa of situation, two different failure rates for stand-by systems must ba considered as follows:

$$R_b(t) = \exp(-\lambda_1 t) + \frac{\lambda_1}{(\lambda_1 + \lambda_3) - \lambda_2} \quad \exp(-\lambda_2 t) - \exp - (\lambda_1 + \lambda_3) t$$

The operating component has a failure rate of λ_1 the stand-by component has an operating failure rata of λ_2 and an idle failura rata of λ_3. Switching reliability is assumed to be unity.

f. Not all reliability problems can be reduced to tha simpla formulas considered hera. Thera ara many new techniques being developed in an effort to obtain valid reliability predictions in complex situations. Some of thesa techniquas include Monte Carlo methods, linear programming, queuing theory, Bayes theorem, and various distribution theories. Markovian techniques, where failure rates changa with times, can be used to consider the affects of component drift and catastrophic failura. (18)

Other advanced analysis procedures are baing developed, but the underlying problem remains in construction of the mathematical modal. The effects of interactions of the outputs of various parts and of their assemblies into sub-systems, may be estimated from the design, or from related test data.

6. Compile Parts Lists--For each block on the reliability block diagram, individual parts should be listed in some convenient order. Parts lists should include part descriptions, pertinent ratings, and space for entering operating voltages, currents, power dissipation, stress indices, and failure rates.

7. Perform Stress Analysis--In a reliability stress analysis, operational parameters such as power, voltage, current, horsepower, system pressure, flow rate, etc., or environmental parameters such as temperature, altitude, humidity, vibration, radiation, etc., are plotted against failure rates. In this report the environmental parameter of ambient temperature plotted against part failure rate will constitute the primary stress analysis. In many instances, operational or environmental parameters are plotted against "application factors" or "operational multipliers." The product of these multipliers and the basic failure rate determines the gross failure rate under particular environmental stresses. Military Standardization Handbook 217 (21) describes in great detail the methods for making stress analysis on electron tubes, semiconductor devices, resistors, capacitors, transformers, inductors, coils, relays, switches and other parts. In using multipliers or correction factors, the failure rate equation normally takes on the following form:

$$\lambda_n = \lambda_o (K_1 \cdot K_2 K_3 K_4 K_5 K_6) \qquad (21)$$

where λ_n is the adjusted failure rate:

λ_o is the basic, or standard failure rate;

K_1 corrects for applied stresses;

K_2 relates the proportion of likely tolerance failures to random catastrophic failures;

K_3 adjusts for changes in external environments;

K_4 is a possible adjustment required to account for different maintenance practices which can have an effect on observed system failures;

K_5 denotes system complexity--the more complex the system, the greater will be its failure rate;

K_6 accounts for observed cycling effects.

Some typical environmental multipliers recommended by Military Standardization Handbook 756 are: (26) p. 318.

Shipborne/Fixed Ground	1.0
Aircraft	6.5
Missiles	80.0
Satellite: Launch: Boost Phase	80.0
Satellite: Orbit Phase	1.0

8. Assign Part Failure Rates or Probabilities of Survival--Failure rates will be extracted from dependable data sources such as FARADA or Military Standardization Handbooks. The stress indices determined in the preceding step will be applied, and if they vary during different phases of the mission will be assigned separately.

9. Combine Part Failure Rates or Probabilities of Survival to Obtain Block Failure Rates or Reliabilities--The mathematical models previously determined are used to combine failure rates into resultant block failure rates. These failure rates are modified to account for tolerance failures and use conditions.

10. Compute System Reliability--System reliability is computed by entering the block reliabilities and failure rates in the system reliability formula and solving for time periods or mission phases of interest. Reliability estimates for the various mission phases should be combined to show system reliability for the entire mission.

Confidence On MTBF Prediction

Frequently the parameter of interest is the Mean-Time-Between-Failures (MTBF), and this can be calculated by evaluating the integral of the reliability function from 0 to ∞ if the system components failures remain exponential. In a nonexponential system, for example redundant systems or systems where wearouts occur, MTBF becomes a function of replacement time (T). An interesting correlation of predicted and actual MTBF's can be seen in the following table: (21) p. 288.

COMPARISON OF OBSERVED AND CALCULATED RELIABILITIES

Equipment	Calculated MTBF In hours	Observed MTBF In hours	MTBF 90% CI Estimate
AIRBORNE			
Weather Radar	366	350	258-508
Fire Control	214	143	106-206
Communications	125	123	112-135
GROUND			
Search Radar	74	63	58-70
Radar Identification	425	339	278-425
Communications	399	439	374-525
Fire Control Display	95	84	66-111
Designation Display	183	185	132-282

The interval of MTBF values given in the last column include the TRUE (but unknown) MTBF 90% of the time for each equipment. These intervals were calculated in accordance with the relationships:

$$\text{Lower Limit} = \frac{2r\ (\text{Obs. MTBF})}{X^2_{\alpha/2}\ (2r)} \qquad \text{Upper Limit} = \frac{2r\ (\text{Obs. MTBF})}{X^2_{1-\alpha/2}\ (2r)}$$

where: r = number of failures observed

Denominators = values from Chi-square distribution table for an alpha = 10% 2r is the number of degrees of freedom.

The observed MTBF was calculated by summing all the operating times accumulated by all the components during the test, and dividing by the number of failures. It should be noted that only two of the predicted values fell outside of the 90 percent CI on the actual test. Both of these estimates were within 8 hours of the estimated CI.

When it is required that a particular system have an MTBF which exceeds a specified minimum value with a probability of $(1 - \alpha)$, i. e., at a confidence level of 100 $(1 - \alpha)$ percent, a one-sided Chi-square test is used. It must be proven that: (1), p. 236.

$$\hat{\theta} \geq C_L \frac{X^2_{\alpha l}\ 2r}{2r}$$

or, that in an accumulated test time of T not more than r failures

$$T = C_L \frac{X^2_{\alpha l}\ 2r}{2}$$

have occurred. Any integer can be chosen for r. Utilizing this information and assuming that the wearout period is normally distributed, it is possible to estimate when the wearout period begins. Reliability is increased and wearouts are eliminated if component replacement or overhaul time is thusly established. For a test truncated after a particular test time the one-sided limit on the estimate of MTBF becomes:

$$\hat{\theta} \geq \frac{2T}{X^2_{\alpha l}\ 2_r + 2}$$

Student's T distribution can be used to determine the limits if a sample size of under 25 is desired in the test.

Truncated testing and small samples may be used to determine estimates of the MTBF, but this causes a fairly large confidence interval as indicated. Another possibility to consider would be a means of accelerating failures of components.

ACCELERATED TESTING

The "race for space" has created a need for refining the process known as accelerated testing. Earlier in the report failure rate data was considered the primary source of information for determining component reliability and consequently system reliability. Because of complexity of systems and changes in design it is often necessary to develop data through testing of devices or systems. Here is an excerpt from a report on the testing being done at General Dynamics, Ft. Worth and its parts venders to insure high reliability on the military's new variable wing aircraft (F-111). (24)

> "The new 'proven performance specs' Military Standardization Handbook 19500, p. 311-324 are based on a concept of 100 percent testing of devices at full-rated power or above for long enough to weed out any failures. Officials at General Dynamics, Ft. Worth are also studying the feasibility of specing integrated circuit functions rather than measuring characteristics of individual components. Some electronic sub-systems used in the F-111 avionics have been on continuous operating test for more than a year without a single component failure."

Two problems become apparent in view of the procedures used at General Dynamics. The first of these is that--specs for integrated circuits or sub-systems have not yet been developed. The second is that as reliability is improved testing becomes an increasingly time consuming process. Mean time between failure must eventually reach the point where the cost of lengthy testing becomes prohibitive. With trips to near planets predicted for the next decade, mean time between failure must be computed in terms of years rather than hours. In order to arrive at reliable failure rate data, or to predict MTBF with any degree of confidence, life testing would require placing the system in operation for a period equi equivalent to the duration of interest. A possible solution to this problem is subjecting electronic sub-systems to accelerated testing techniques.

One form of accelerated testing employs high stresses to accelerate failure. By applying a factor which relates stress and lifetime, it can be determined in a short period under high stresses what may be expected to happen in a much longer time under normal stresses. Some of the problems encountered with this type of testing include:

1. The correctness of the stress-like relation for the components or sub-systems.

2. The equivalence of the unit tested to the unit actually used.

3. The correct evaluation of effects of simultaneously combined stresses in their related magnitudes.

4. The size of the sample tested and the variability of the results.

Another form of accelerated testing requires testing an increased number of components in order to obtain in a short time a large number of component operating hours. The difficulty encountered here is that inferences about life distributions must be made from truncated samples which often can lead to erroneous predictions.

The use of accelerated tests is often proposed to reduce testing time and testing costs. The procedure is to determine failure rates under high-stress conditions and extrapolate the results to give an estimate of anticipated failure rates under use conditions. Studies are now being carried on by various manufacturers, and experience indicates a high degree of difficulty in obtaining precise acceleration factors for most electronic parts. (19)

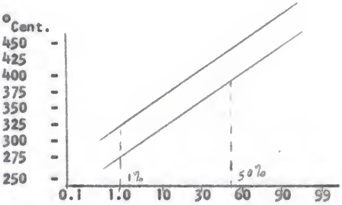
One of the most thorough studies run so far in the field of accelerated testing techniques was accomplished by the General Electric Company on Contract AF 30(602)-3415. (27) The purpose of that program was to study, investigate and develop the testing and measurement techniques for controllable accelerating of electronic parts aging; and to perform an investigation study and analysis of the failure mechanisms of the high reliability parts used. In the test, externally produced thermal energy was selected as the degradation stress for resistors and semiconductors. This selection was based upon the fact that changes in the electrical properties of these types of electronic parts, with respect to time, are the result of chemical and physical changes. These reactions usually are accelerable by application of thermal energy. Since thermal energy was selected as the degradation inducing stress for the majority of the tests, it was necessary to precisely control and measure the critical element temperature. This was done by using ovens with a $\pm 2^{\circ}$ C temperature control, and the use of a nitrogen atmosphere to retard oxidation of the leads. An upper limit of 350° for resistors and 300° for semiconductors was set because changes in failure mechanism were observed at higher temperature. Average rates at which the parts failed were determined by a series of accelerated tests-to-failure. These results were used to establish life characteristics with statistical confidence limits. One of the methods for establishing life characteristics is the step stress technique.

Step Stress Technique

The step stress technique for accelerated testing consists of considering stress as the independent variable and some function of damage as the dependent variable of deterioration. The procedure is to start at a stress level where deterioration is known not to be significant and increasing stress in increments until deterioration, observed in terms of damage, becomes significant.

The accelerated step stress tests for the semiconductors in the General Electric study indicated an excellent means of determining long life capability of parts. Using step stresses of 24 hours and 120 hour duration and samples of 50 R2008P5 diodes, a plot of junction temperature versus the normal probability scale was made as indicated below: (27) p. 2.29.

Junction Temperature
1/Tabs.

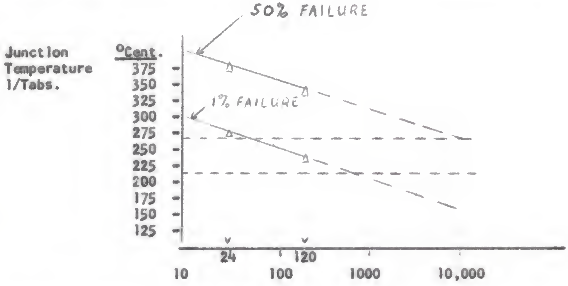


NORMAL PROBABILITY SCALE

Selecting the 1 percent and 50 percent failure points for each phase test, these points were replotted on a junction temperature versus log time scale. Linear extrapolation shows a 1 percent failure occuring at about 8000 hours. The overall study concluded that a definite correlation could be established between accelerated tests and life tests provided a damage parameter can be determined for parts which will be linear when plotted against degrees centigrade on a 1/T Kelvin Scale.

The above information can best be illustrated by the following table:

(27) p. 2.29.



TIME-HOURS TABLE

Assuming an exponential reliability function, an acceleration factor can be established from the following:

$$A = e^{-t\left[\left(\lambda(T_o) - \lambda(T_1)\right)\right]}$$

where $\lambda(T_o)$ = failure rate at use temperature

and $\lambda(T_1)$ = failure rate at accelerated temperature

> "There is much evidence (11) to conclude that $\lambda(t)$ is a linear function of the reciprocal of the operating temperature T in degrees Kelvin, therefore--
>
> $$\lambda(t) = A + b/T$$
> or
> $$\lambda(T_o) - \lambda(T_1) = b\left(\frac{1}{T_o} - \frac{1}{T_1}\right)$$
>
> Therefore, if the degradation rate (b) can be estimated from experimental data the acceleration factor (A) is easily determined.
>
> For the Weibull distribution it can be proven that the acceleration factor is:"
>
> $$A = e^{b}\left(\frac{1}{T_o} - \frac{1}{T_1}\right)$$

and it is independent of time. Again if the degradation rate (b) can be determined then (A) can be found. Proof of the derivation of this can be found in RADC-TDR-64-142. The author assumes that B is relatively independent of temperature. (1)

Matrix Testing

Another convenient method of determining acceleration factors is described by P. H. Greer (11). Greer uses a "matrix" type experiment in which combinations of environmental conditions such as temperature, voltage, and power are used to stress the units. The proportions defective under each condition of stress are estimated and regression techniques are used to estimate reliability factors over a large number of stress conditions.

A matrix test which was developed by Motorola as a part of Minuteman Transistor Reliability Improvement Program is shown below. The program consisted of testing a number of devices at several combinations of ambient or case temperatures, and percentages of rated power to accelerate the potential device failure mechanisms. A total of 9,675 devices were tested at power levels from 0 to 133 percent of rated dissipation and under eight ambient temperature conditions for 4,000 hours.

Failure rates were plotted against junction temperature on a $1/K^{o}$ scale and the plots formed a straight line. Higher failure rates occurred for the 15V test than for the 5V test, indicating that this type of device is affected more by the voltage field effect than by current density. However, the slopes of the 5V and 15V plots were approximately the same. From the failure rate plots, it is possible to determine an acceleration factor at any test condition. One important precaution which must be observed in matrix testing as well as any other accelerated test plan is the assurance that no new failure mechanism is introduced. If the increased stress tests introduce new failure mechanisms, then the validity of predicting long-term life reliability is lost. Matrix testing then is another means of determining acceleration factors: (11) p. 10.

MATRIX FOR RELIABILITY TESTING

% of Rated Power / Ambient Temperature	0	33	66	100	133
Volts	0	5 15	5 15	5 15	5 15
25° C		3000	1000	400	200
50° C	1500	1000	400	200	150
75° C	500	400	200	150	100
100° C	200				
125° C	100				
150° C	75				
175° C	50				
200° C	50				

NOTE:

Quantities of devices shown in operating cells were equally divided between the two voltage levels used.

Some of the conclusions made by Motorola as a result of their Accelerated Life Tests warrant consideration here. (11), p. 145.

1. Accelerated life testing can be used to develop mathematical models from which the failure rate at any desired time and temperature

can be computed with relatively good correlation with observed results.

2. Matrix type stress testing appears to have considerable value as a means of obtaining information regarding the effect of time and temperature on failure rate.

3. Standard sequential step stress testing is not consistently adequate for establishing acceleration factors between short term testing (14 hour to 56 hour intervals) and long term testing (1,000 hours) of the Motorola PNP silicon expitoxial planer 2N1132 transistor. It is very probable that the cumulative effects of both time and previous stress levels, which occur in sequentially step stressing the same devices, sometimes hide true failure rate indications.

4. The sequential step stress testing technique is very effective in comparing the relative reliability of two or more samples.

Other sources agree on the determination of acceleration factors, but doubt the feasibility of using accelerated testing on complex devices. Their conclusions are based on the current lack of knowledge regarding statistical handling of competing failure risks. (28)

Before attempting any accelerated testing approach certain areas of knowledge must be established:

1. Knowledge of the modes of failure and their physical causes that occur at usage conditions.

2. A sufficient knowledge of the dependency of failure behavior on experimental conditions to justify an extrapolation from accelerated conditions to usage conditions.

If this knowledge can be attained, and assumptions regarding forms of failure distributions and relations of distributions to environmental conditions can be made, accelerated testing can become an effective prediction tool.

AN AIRBORNE ELECTRONIC SYSTEM EXAMPLE

Utilizing the background information described here it would be possible to construct a program to test the feasibility of predicting MTBF for systems by experimenting with various environmental conditions. Following the reasoning established by General Electric in RADC-TDR-64-481 (27) thermal energy was used as the discriminating environmental factor. A module from an airborne equipment with component parts known was constructed.

Analysis of Data

Failure rate data for the component parts was obtained from Military Standardization Handbooks, and from the company producing the parts. For the particular module under consideration, Collins Radio Company supplied the failure rate curves based on information from the following sources: (13)

1. Actual experienced part failure rates were obtained from SAC Ground Station Control Center equipment with a total accumulated time of over 1.7 billion part-hours.

2. Numerous part vendors.

3. Military and civilian study programs such as the RADC Reliability Notebook, section 8, and the Vitro Technical Report 133. These Failure rate curves were constructed using the most influential stress factor, thermal energy, as the independent variable. If thermal energy

was not the only dominating factor, several curves were added at various levels of the other stress factor. Stress factors used in this report were:

PART TYPE	FACTOR(S)
Electrolytic Capacitor	Body temperature
Ceramic Capacitor	Voltage and Body Temperature
Mica Capacitor	Voltage and Body Temperature
Paper Capacitor	Voltage and Body Temperature
Diode	Junction Temperature
Transistor	Junction Temperature
Transformer and Inductor	Hot-spot Temperature
Relay	Contact load and duty cycle
Composition Resistor	Body Temperature
Film Resistor	Body Temperature
Wire-wound Resistor	Body Temperature
Tube	Power Dissipation and Bulb Temperature

In considering stress factors, the hot-spot temperature was found by the change-in-resistance method (Mil-T-27A) using the following formula:

$$T_{hs} = \frac{R - r}{r}(T + 234.5) + 2t - T \text{ in centigrade}$$

where T_{hs} = hot-spot temperature

t = ambient temperature prior to power application

T is the ambient temperature after power application

r is the winding resistance taken at t

R is the winding resistance at T

For determining the junction temperature of a semiconductor, the case temperature is added to the product of the power dissipation and the thermal resistance.

$$T_j = T_c + PK$$

Computational Techniques

Making the same assumptions described previously concerning early failures and wearout failures the MTBF can be predicted mathematically by a summation of the predicted part failure rates. Since failure rates are frequently displayed as percent failures per 1,000 hours, the method for determining MTBF is:

$$\theta = \frac{10^5}{\lambda_1 + \lambda_2 + \lambda_3 + \cdots \lambda_n}$$

The table indicating part types, nominal operating levels and failure rates for the airborne module under consideration is shown on the following page. From this table it can be determined that MTBF will be:

$$\theta = \frac{10^5}{6.47} = 15,456 \text{ hours}$$

Using increased ambient temperatures of 10°, 20°, 30° and 40° above normal it was possible to predict MTBF's of the module at increased temperature levels. The failure rate data was extrapolated from the failure curves given for environments of military airborne, commercial airborne and fixed ground units. The MTBF's computed at each of these levels is indicated below:

	Nominal	$+10^\circ$	$+20^\circ$	$+30^\circ$	$+40^\circ$
Military Airborne	15,456	11,910	7,710	5,351	3,456
Commercial Airborne	24,640	23,420	14,918	11,210	8,610
Fixed Ground	42,800	34,000	24,100	16,050	10,340

SYSTEM FAILURE RATE DETERMINATION

Part Type	Application Factors	Failure Rate	QTY	Total
Electrolytic Capacitors	Body Temp-65 C	.125	2	.250
Ceramic Capacitors	Body Temp-40 C	[illegible]	6	[illegible]
	Voltage-.6 Rated	.0095	6	.057
	Voltage-.8 Rated	.023	2	.046
Paper Capacitors	Body Temp-45 C Voltage-.5 Rated	.018	3	.054
Germanium Diodes	Junction Temp-50 C	.110	2	.220
	Junction Temp-75 C	.480	1	.480
Chokes	Hot-Spot Temp-50 C	.152	3	.456
Gen Purpose Relays	Contact Load-.5 Rated Duty Cycle 3/Hour No. Contact-2 sets	.27	2	.540
Wire-Wound Resistors	Body Temp-100 C	.0027	2	.005
	Body Temp-125 C	.0075	1	.008
Audio Transformers	Hot-Spot Temp-70 C Insulation Class-B	.175	1	.175
Composition Resistors	Body Temp-40 C	.0068	5	.034
	Body Temp-55 C	.0102	4	.041
	Body Temp-65 C	.013	2	.026
	Body Temp-80 C	.0195	1	.020
Miniature Tubes	Bulb Temp-100 C Power .6 Rated Heater Voltage .9	.835	2	1.670
	Bulb Temp-150 C Power Rated Heater Voltage .9	2.262	1	2.262
Composition Potentiometers	N/A	.033	2	.066
	Total Electrical Part Failure Rate		=	6.410
Mech Parts		.012	5	.060
	Total Equipment Failure Rate		=	6.470

The data compiled was fed into the computer in an effort to determine the function representing this relationship. If it is assumed that the exponential distribution is continuous for all environments then an acceleration factor (K) can be determined by:

$$K = \frac{\theta i}{\theta_j}$$

where θ_i = MTBF for environment i

and θ_j = MTBF for environment j

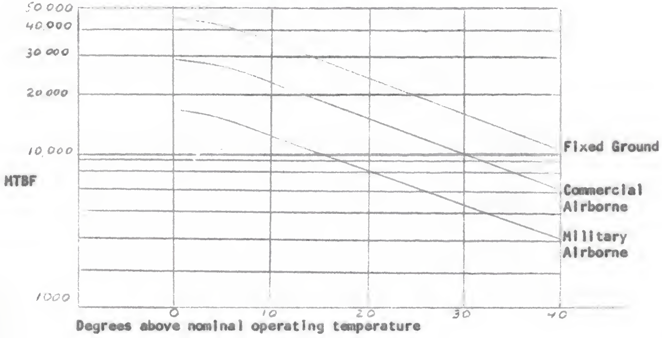
Therefore, testing at 40° above nominal on military airborne equipment

$$K = \frac{15,456}{3,456}.$$

The function developed by the computer for this airborne module was the following:

$$\theta = .99875\ (T)^2 - 329.5T + 14,660$$

where θ = MTBF and T = degrees centigrade beyond nominal operating temperature. From the graphs below it can be seen that the various thermal stresses produce a family of curves.



As described previously, if all assumptions are valid, actual MTBF should fall within the 90 percent CI of the predicted MTBF. Using these curves and their related environmental conditions the data collected can now be used to illustrate the prediction of MTBF for a particular piece of electronic equipment. If the steps as outlined in this report are followed, the listing of component parts and their environmental conditions must be compiled. From this list, and a knowledge of nominal operating temperatures, it is possible to determine the failure rates at any temperature level within operating limitations. For the device in question, MTBF at use conditions was predicted to be 15,456 hours. From the same failure rate data it was predicted that the MTBF at 40° above nominal temperature was 3,456 hours. The plot of these MTBF versus temperature levels above nominal range approximate a linear relationship. If this can be assumed, the method for determining acceleration factors as described earlier in this report can be applied.

In order to verify the above mathematical analysis, it would be essential to actually test the proposed system using the step stress technique at various increased temperature levels. Using a sufficient number of samples to substantiate actual failure rates, the MTBF's can be determined by Method 2 described in this report. Assuming the actual MTBF's correlate with the predicted MTBF's at all temperature levels it would be safe to say that the procedure of extracting part failure rates at increased stress levels to determine MTBF of a subsystem at use conditions is feasible.

The electrolytic capacitors limit this particular system from being tested at a higher stress level, but other systems could be tested at much higher stress levels. Normally, the failure rate data information will indicate a maximum operating stress condition.

From the time to failure at increased stress level, confidence limits could be predicted for the module at use conditions as described earlier in this report. If the system was of a new design and the mathematical model was extremely complex, the method of step stress testing at increased temperature levels could be used. Assuming that the characteristics of the components were not exceeded a system MTBF curve could be established and a relationship determined. Like systems should have similar MTBF's and consequently these should be predictable at various use conditions.

CONCLUSION

The conclusion arrived at in this study is that accelerated testing of electronic systems appears unfeasible. For the particular test run in this study, many assumptions were made that very seldom hold true in light of the complexity of modern electronic systems. The possibility that there is no interaction between component parts or that systems can be broken down into independent sub-systems seems highly improbable. Although temperature was used as the primary stress in this study, it is well known that various components react more vigorously to other environmental stresses. Most authors will agree that the many different environmental stresses encountered during various phases of the life of an equipment are practically impossible to completely simulate. The study carried on in this report assumed one constant environment and did not include any determination of off duty failure rates. Another i-important consideration concerning failure distributions was included in the study to compare more complex functions with the exponential. One of the most critical factors in carrying out a prediction study from accelerated stresses pertains to the maximum operating limitations of the component parts. Parts manufacturers all agree that, if their components are used above the specified limits, failure rates can not be predicted. With this limitation, stress levels often can not be raised enough to be truly effective. Another problem encountered in verifying the method proposed in this study would be the difficulty in placing the cause of failure on a particular part. Miniaturation of today's electronic systems creates an almost impossible task of monitoring degradation rates.

As pointed out in the study, temperature and atmosphere control must be carefully controlled even in a simple test. All other environmental conditions and stresses would also have to be carefully monitored to avoid the inclusion of erroneous data. A possible solution would be the use of computer simulation techniques through a matrix type study of various stresses. If samples of electronic systems can then be tested and results compared with simulation techniques, a possible solution may evolve.

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PREDICTION OF MEAN TIME BETWEEN FAILURES OF ELECTRONIC SUBSYSTEMS FROM COMPONENT FAILURE RATES DETERMINED UNDER VARYING ENVIRONMENTAL CONDITIONS

by

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B. S., United States Military Academy, 1956

AN ABSTRACT OF A MASTER'S REPORT

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The primary objective of the study carried on in the preparation of this report was to provide an assessment of the feasibility of predicting the reliability of electronic systems through the analysis of failure rates under accelerated environmental conditions. The report contains four major sections describing (1) some basic fundamentals of reliability theory, (2) methods of predicting reliability, (3) various types of accelerated testing, and (4) a typical example of predicting the mean time between failures of an airborne electronic system. The specific intent of the latter item was to validate procedures for determining the mean time between failures of an electronic system under accelerated thermal stresses, in an effort to predict the mean time between failures of the system under use conditions.

The conclusion arrived at in this study was that the accelerated testing of large scale systems appears unfeasible because of the complexity of the systems and the inaccuracy connected with breaking systems into sub-systems. Although temperature was used as the dominating stress in this study, it is known that various components react to other stresses more vigorously and that all components do not fail exponentially. Different failure distributions were discussed to provide an indication of the complexity of developing a mathematical model to apply to a system. Another problem area, in testing complete systems, stems from the fact that certain elements such as electrolytic capacitors have maximum temperature operating ranges quite low. This would prohibit any testing at levels high enough to be effective. With the miniaturation of today's electronic systems, responsibility for failure would be extremely difficult to pin-point. Interaction of devices at accelerated conditions would have to be thoroughly studied and a means of monitoring each individual component would have to be established.

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