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68-273

Literature Review Study on Accelerated Testing of Electronic Parts

(Final Report)

ACCELERATED TESTING OF ELECTRONIC PARTS

Dr. Ralph A. Evans

April 1968

Prepared for
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103
Under Contract #951727

N68-36621 (ACCESSION NUMBER) (THRU)
114 (PAGES) 1 (CODE)
CR 97207 (NASA CR OR TMX OR AD NUMBER) 09 (CATEGORY)
FACILITY FORM 602

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FOREWORD

This final report was prepared under Contract #951727 issued by the California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California. Mr. Ervin Klippenstein is Contract Monitor, Dr. R. M. Burger is Project Director, and Dr. R. A. Evans is Project Leader. The work was performed in the Engineering and Environmental Sciences Division of the Research Triangle Institute.

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, pursuant to a subcontract issued under Prime Contract NAS7-100 between the California Institute of Technology and the United States of America represented by the National Aeronautics and Space Administration."

ABSTRACT

This report discusses the four kinds of uses to which accelerated testing is put; three of them are qualitative, and the fourth is quantitative prediction. The concepts necessary to understand the philosophy of accelerated testing are explained, eg, true acceleration, failure modes and mechanisms, and conceptual models. The different ways of programming the severity levels in an accelerated test are listed. The main ones are constant-'stress' tests and step-'stress' tests. In order to compare these it is necessary to have some theory of cumulative damage. The linear theory is most common but not most accurate. Thermal acceleration is by far the most usual and easy way of accelerating a test. There is no magic, ideal formula to which properly made things must conform but there are useful equations, the Arrhenius being the most ubiquitous. After having run an accelerated test most everyone wishes to extrapolate to the usual conditions and the dangers inherent in this process are explained and evaluated. This is followed by brief discussions on how the accelerated testing has been handled in the literature for resistors, capacitors (dielectrics), discrete semiconductors, and integrated circuits. These sections are short since the principles have been covered in the earlier general chapters. Discussions of mathematical details and specialized techniques are included in the appendixes.

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ACCELERATED TESTING OF ELECTRONIC PARTS

Final Report

1. Introduction

This report is a tutorial exposition on the state-of-the-art of accelerated testing of some electronic parts, viz, resistors, capacitors (dielectrics), discrete semiconductors, and integrated circuits; it is based in part on a survey of the literature. The scope, determined by contractual requirements, includes: listing the literature reviewed during the contract; summarizing each approach used in accelerated testing; comparing the test designs, testing methods, mathematical models, and test programs; evaluating the extent of success and applicability of each approach. The text can be taken as a guide to the philosophy of accelerated testing and as an explanation of the trade-offs which must be made when using it.

Accelerated testing is a very loosely defined concept; attempts to make it rigorous generally run into problems. Loosely speaking, accelerated testing started when someone said, "Let's shoot the juice to it and see what happens." This means, roughly, "Let's treat it worse than we expect it to be treated in ordinary practice and then see what happens." One difficulty is that treating-it-worse does not always mean "shooting the juice to it". For example, electrical contacts behave better as voltage and current are increased (up to a point) and some warmth may improve matters for electronic equipment by helping to reduce the moisture problem.

Accelerated testing in this qualitative sense is something that anyone can do and that everyone does. There is a reasonably firm qualitative foundation for much of it. It is in the quantitative interpretation that troubles begin. These qualitative and quantitative uses of accelerated testing can conveniently be put into four classes:

1) qualitative--to see what kinds of failures are generated and to decide then if a modification is worthwhile.
2) qualitative--to get a rough, quick idea of whether or not something can stand the gaff.
3) qualitative--to see what happens when the user maltreats the device as he probably will.

4) quantitative--to make a prediction about the life under actual operating conditions.

There is little question that accelerated testing is useful for the three qualitative measures; so it is mainly the quantitative problem to which this report is addressed. This is not to demean the other three; they merely lie outside the scope of the report. The use of accelerated testing for the first three purposes should be encouraged because it does give valuable additional information when compared to not running any such tests.

Section 2 discusses in detail some of the concepts which are important in accelerated testing. Section 3 analyzes the various ways in which the time sequence of stresses or severity levels may be conveniently arranged in an accelerated test, how these different tests can be related, and ways in which more than one component of a severity level can be changed at one time. Section 4 is concerned with equations ordinarily used for temperature acceleration. These have a chapter by themselves since this kind of acceleration is so important and widespread. Section 5 is a brief discourse on the problems involved with extrapolating equations beyond the range where there are data. Section 6 gives a summary of each of the approaches used in accelerated testing and some idea of the extent of success and applicability that each approach has had. The next four sections consider the ways in which testing is accelerated for each class of part. It compares the test designs, testing methods, mathematical models, and test programs for each part. The report is concluded with the usual recommendations and conclusions. The appendixes give some of the mathematical techniques and details which may not be familiar to the reader.

The ideas of a conceptual model and of models vs reality are important to the point of view pervading this paper. Therefore Sec. 2.1 (Models) should be read carefully.

2. Concepts

2.0 There are several concepts which are used in any discussion of accelerated testing and about which there is some confusion. It is the purpose of this chapter to discuss those concepts and give them fruitful meanings.

2.1 Models

The idea of a conceptual model is adapted from the idea of a physical model such as a model car or the model of a building. In a physical model, the characteristics of importance to us are reproduced quite well. In a model car these might be proportions, shape, and color. The characteristics of little or no importance are not usually reproduced at all; eg, there may be no motive power and the tires may not be pneumatic. The "inbetweens" receive indifferent treatment, eg, the windows may be transparent and the presence of seats inside may be inconsequential. The physical model is an abstracting of something important from the real world; it is an imitation.

A conceptual model is analogous to a physical model. Since everything in the universe probably affects everything else to some degree, however slightly, any exact treatment would be hopelessly complicated. Therefore we decide how we will look at the situation and make a set of assumptions (both explicit and implicit) about what we will ignore and what we will include in our conceptual model. It is usual to state only a few things that are being ignored and to make the blanket assumption that everything else which is not explicitly mentioned is also to be ignored. By its very nature, a conceptual model is incomplete: it ignores some things and describes other things in an approximate fashion.

After having made a set of assumptions for a conceptual model, we then operate on those assumptions with mathematics and logic; we analyze them by any means at our disposal. The assumptions together with the current results of the analysis are our model. While developing the logical implications of a set of assumptions, we often don't like the results for one reason or another: they don't seem to fit, they appear to be inconsistent with our beliefs, etc. Under these circumstances we have two rational choices:

1) change our beliefs about the way the world is, if we are convinced that the set of assumptions are very realistic; and/or

2) go back and modify the assumptions so that their logical implications do in fact fit our beliefs about the world.

The creation of a conceptual model is a circular, often haphazard, process wherein ideas come from everywhere and get analyzed, tested, compared, junked, and accepted. Some good ideas usually filter through the process.

The completely logical structure of a conceptual model is developed after an idea is successful. Some of the ramifications are so complex that it takes much calculation to find out what they are--thus the science of simulation. Sometimes we refer to one equation or curve as the model, but this is just speaking loosely.

If a model fits the real world well enough for our purposes at the moment, it is an adequate model for the moment. Adequacy depends not only on the model and on the world, but on our needs and desires--not to mention our ability to compare the model with the world. Thus models are not right or wrong but only more or less adequate. Of course, some models are so woefully inadequate for anything that we class them as wrong. Others are so generally adequate that we feel they correspond very closely to reality. In this latter case, however, it is important to distinguish between a definition and a model; the reason some "models" do so well is that they are, in fact, definitions of some of the quantitities or concepts involved. For example, "An unbiased coin toss will have a 50-50 chance of heads or tails" is not an assertion about the world, but a definition of "unbiased coin toss". If it doesn't come out 50-50, we don't change our ideas about what unbiased coin tosses do, we search for the bias in the coin toss.

WE NEVER ANALYZE THE REAL WORLD, WE CAN ONLY
ANALYZE A CONCEPTUAL MODEL OF THE REAL WORLD.

An engineering model is often mathematical in nature and the same formalism will describe several different situations. For example, the equations which describe resistance-inductance-capacitance networks will also describe mass-spring-dashpot systems. Furthermore, there is more than one analogy between the two that can be made. It is important to keep the distinction between the mathematics itself (which is quite general, completely impersonal, and always true) and what we have it represent in an engineering sense.

The term probabilistic-model appears in the literature (but not here). It is generally a special case of mathematical model wherein the relationships are between probabilities or between random variables.

The word, theory, has not been used in this section although some people would describe a conceptual model as a theory. While the correspondence can certainly be made there is more to communication of ideas than a strict definition. The word, theory, often connotes a true theory and the word, ideal, is used to refer to some aspect of a theory. The difficulties are illustrated by the phrase, "It may be true in theory, but it's not true in practice." The fact that this remark is often made shows the inadequacy of the terms. Most tractable models are gross abstractions from the world. They are rarely very sophisticated or complete because if they were, they would no longer be tractable. Terms which are descriptive and have useful connotations are "simple-minded model" and "moronic model". Thus instead of saying, "Theoretically, birds can't fly." or "I have proved that birds can't fly." one would say, "According to my simple-minded conceptual model of a bird it can't fly." Most of the uses of the term "ideal..." are now replaced by "simple-minded" or "moronic conceptual model". For example one might have said that the ideal electric motor has perfect bearings, perfect heat conduction, etc. A much better phrase is that a moronic conceptual model for a motor has these properties.

Where there is little possibility of confusion, the adjectives "physical" or "conceptual" are dropped and "model" is used by itself.

2.2 Failure models

2.2.0 Many failures can be grouped into simple categories. For example, in some situations the application of a stress does not produce damage as long as the part has not failed while in others the application of a 'stress' produces damage cumulatively with time, and the damage remains, even after the 'stress' is removed. Obviously not all failures can be uniquely classified into simple categories, but their use helps to organize the ideas and thus make them easier to use.

2.2.1 Simple stress-strength model for failure

The simple stress-strength model for failure is patterned after the failure of structural metals in uniaxial tension. There is a value of stress called the strength such that there is failure if and only if the instantaneous stress[1] exceeds the strength. If a stress less than the strength is applied and removed, no damage is done and the strength remains the same. The general model is: there exist a scalar (S), which can only depend reversibly on the environment of the part, and the value (S^*) of that scalar such that the part fails if and only if $S > S^*$; S^* is then the strength. Values of $S < S^*$ do no damage to the part; in fact damage less than failure has no meaning.

There are not many examples of this model in electronics. The voltage breakdown of semiconductors is one, and some claim that very short term breakdown of capacitors is another. Most of the others involve cumulative damage.

This model of failure is not ordinarily concerned with accelerated testing although some people include it in their test-to-failure classification. For example, instead of just testing to the working-stress or to a proof-stress one actually measures the strength of the part and thereby gets more information.

2.2.2 Simple damage-endurance model for failure

The terms stress and strength are not used in this section since they are commonly associated with the simple stress-strength model described above. The simple damage-endurance model for failure asserts that the application of a damager causes cumulative damage in some way and that some of the endurance of the part has been consumed even if failure does not occur. When the damager is removed the damage is not undone; the damaging effect is not reversible in the ordinary sense (although

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[1] The word, stress, in this text is not used to cover the situation wherein cumulative damage occurs; therefore stress is synonymous with instantaneous-stress and will be used instead because it is shorter.

negative-damage can be done and is often called annealing). A general, albeit simple-minded model, for cumulative damage can be established: there exist a scalar (D), which depends on the set of damagers and on their behavior over time, and a value (E) of that scalar called the endurance such that failure occurs if and only if $D > E$. It is often difficult to know how to express D and E. A very common procedure is to give the value 1 to the median endurance and to describe the damage D as the fraction of median life that has been consumed.

Unfortunately D or E-D is virtually impossible to measure. There are two simple-minded ways of estimating it:

1) Find a failure mode which fits the simple stress-strength failure model and measure the strength. Or
2) Continue applying the damager until failure occurs. The amount of time to cause failure taken by a particular damager level is then a measure of E-D.

Unfortunately there is no guarantee that high values of strength in #1 correspond uniquely to high values of E-D in #2.

This simple damage-endurance model is the one most often assumed in accelerated testing. So in this report the words, damager, damager level, or severity level, will be used as appropriate rather than stress, in order to distinguish easily between these two simple models for failure rather than to confuse them as is so readily and often done.

2.2.3 Strength degradation failure model

A failure model found occasionally in the literature combines the stress-strength and the damage-endurance concepts. The effect of a damager is considered to be the reduction of strength for a simple stress-strength model. In some cases the damager which causes the reduction in strength is the same as the stress which will cause failure when the stress exceeds the strength. In other cases the damager is completely foreign to the stress. Examples are easier to visualize in the mechanical or electro-mechanical fields, where these concepts are better established than in electronics.

Consider a steel bar. Let the stress for the simple stress-strength model be tensile stress and the strength be the ultimate tensile strength.

If the damager is a fatigue stress, for example, it will be of the same kind as the stress that is going to cause failure. On the other hand, if the damager were a corrosive environment, the damager would be completely unlike the stress that is going to cause failure.

2.2.4 Hazard rates and damage

One cannot discuss the relationship of damage and hazard rate[2] without some knowledge of the environment. If the environmental severity is constant with time and if damagers are present, the element will probably eventually fail due to those damagers[3]. The endurance of an element is generally a random variable since not enough information is available to describe it accurately. For a constant hazard rate process with constant environmental severity, damage is done as time goes by; therefore a used element is not as good as it was itself when new. But since we do not know the life of the individual element, the distribution of element lives can be such that any element known to be good is as likely to last as long as any other element known to be good whether new or not. If the hazard rate is decreasing continuously we have the apparent anomaly that, even though the element itself is being degraded, as long as it has not failed it is more likely to last longer than one which has not been operated. The explanation of course is that we do not know what the starting endurance of each element is. If we did, the endurance would no longer be a random variable and we would know the life of each one to begin with. Then the cumulative hazard function would be either 0 or 1 and the hazard rate would be a spike at the changeover. This illustrates the difference between 1) considering an individual element and 2) making probability statements which, even though made about an individual element, are effectively relative frequency observations about the population to which the part belongs (they could also be interpreted as subjective probability).

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[2] Names, definitions, and illustrations related to reliability and hazard rate are given in Appendix A. Graphical estimation of hazard rate is discussed in Appendix B.

[3] In metal fatigue the presence of a damager does not always cause failure. In various materials, eg, steel, there is a fatigue limit below which a cyclic stress will not cause failure.

2.3 System state

The state of a system is not uniquely defined for a physical system; it is defined only for a conceptual model of the system. The detailed specification of the system state will vary with our needs and desires and with the required tractability of the resulting equations. The state of a system will ordinarily have several dimensions (components); so it can be classed as a vector. For example, consider a resistor. If we are concerned only about its resistance and nothing else, then the state of the system will be given by the resistance of the device (or something equivalent thereto such as a ratio of the resistance to an initial resistance). On the other hand, we may be concerned about the resistance, the temperature coefficient of resistance, the voltage coefficient of resistance, and the chemical composition of the resistive material. Then there will be several dimensions for the system state, and two states will not be the same unless all corresponding dimensions are pair-wise the same.

Lest one be concerned that associating a system state only with a system model rather than with the system itself is too sloppy, an analogy can be made to thermodynamics. There can be many thermodynamic models of a system depending on what is of concern. The entropy is not defined for the system itself but only with regard to a particular thermodynamic model of that system.

The state is usually denoted by a vector, eg, $\underline{S}$.

2.4 True acceleration

Several definitions[4] for true acceleration appear in the literature, some of which are not very explicit. Most engineers associate true-acceleration with behavior over time. The one given below is chosen for its generality and applicability. Note well, however, that acceleration need not be true to be useful even though untrue acceleration is more difficult to analyze, even qualitatively.

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[4] One very poor choice is to assert that acceleration is true if and only if it follows the Arrhenius equation. Another poor choice is to associate it with the constant hazard rate.

Acceleration is true if and only if the system, under the accelerated conditions, passes reasonably[5] through equivalent[6] states and in the same order it did at the usual conditions. Let $\underline{g}(t)$ be the state of the system under usual conditions and let $\underline{G}(t)$ be the equivalent state of the system under accelerated damagers ($\underline{G}$ is not the state at the accelerated conditions but is the state after being transformed reversibly down to the usual conditions). Then there is true acceleration if and only if

1) $\underline{G}(t) \equiv \underline{g}(\tau[t])$;
2) $\tau(t)$ is a monotonically[7] increasing function of the argument;
3) $\underline{G}(0) = \underline{g}(0)$; and
4) $\tau(0) = 0$[8]

The acceleration factor (A) is defined as $A(t) \equiv \tau(t)/t$. An incremental acceleration factor may be defined as $\tilde{A}(t) \equiv d\tau(t)/dt$. True acceleration

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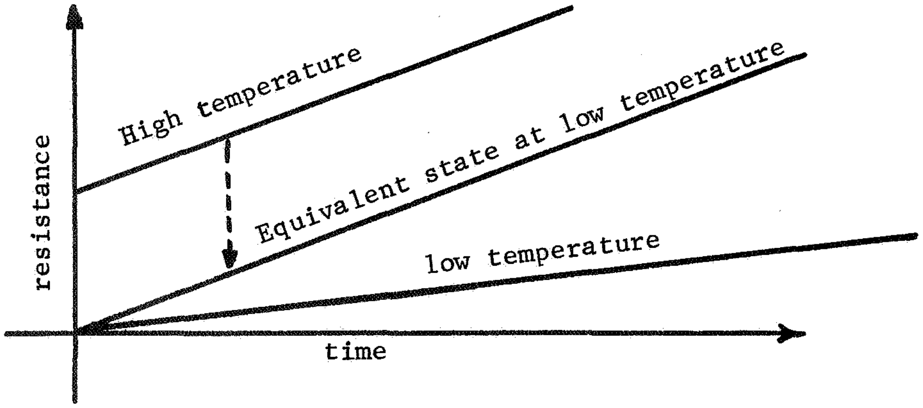
[5] The word "reasonably" is necessary because the needs and desires of the situation may be different from time to time, and as engineers, if things are close enough for the purposes at hand, there is no need to worry about the discrepancies as far as these purposes are concerned.

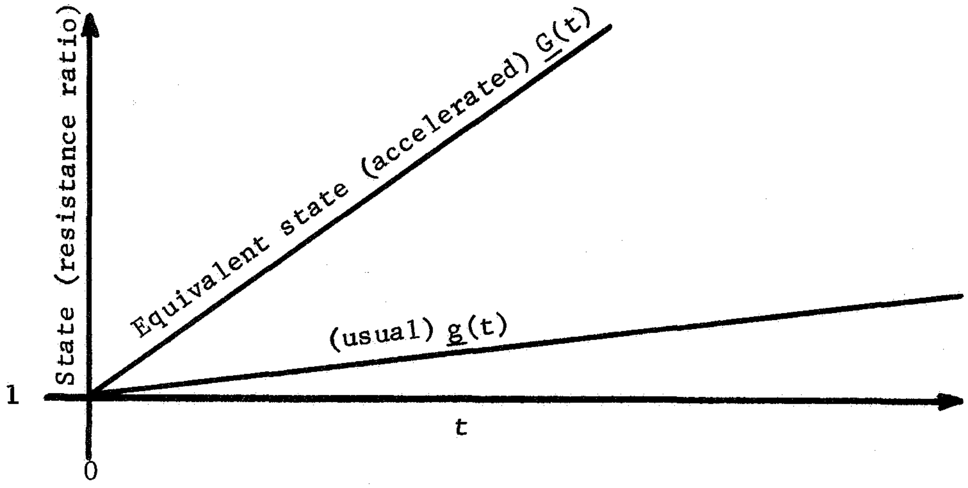
[6] Two states of a system are equivalent if and only if one can be reversibly transformed into the other by changing the environment. For example, a resistor at a higher temperature might never have the same resistance it would at a lower temperature, solely because of its temperature coefficient. This is illustrated in the figure.



[7] For those who think the term is ambiguous, monotonic is used here in the strict sense, viz, staying constant is not allowed.

[8] If $\underline{G}$ and $\underline{g}$ have a one-to-one correspondence with the argument (the reciprocal function exists), this is a logical consequence of #1 and #3.

is illustrated in the figure for a state vector with a single dimension--resistance ratio of a resistor.



$G(t) = 1 + 60\ a\ t,$ $g(t) = 1 + 10\ a\ t,$ (a is some constant)

$\tau(t) = 6t;\ A = 6,\ \tilde{A} = 6.$

It is of course nice if A(t) is a constant with respect to time as in the figure and depends in some quite tractable way on the severity level.

Estimates of an acceleration factor will depend on the statistical procedures used to arrive at them.

It is important to recognize the arbitrariness of the definition especially as regards the word, reasonably. In order to have true acceleration it is only necessary that the things in which we are immediately interested be close enough under the two sets of conditions. To be specific, not all failure modes and mechanisms need be identical down to the last electron orbital.

Generally the physical condition of the device will be included in the system state either explicitly or implicitly in sufficient detail to permit judgments to be made about its design and construction relative to the failure modes and mechanisms.

2.5 Stress, damager, severity

Many general words have been preempted by some segment of engineering to have specific technical meanings. So it is sometimes difficult to find good ones for a general purpose. Reliability is one of the foremost examples of a once general word which has been set aside to have a very specific meaning.

The word, damager, is used in this report when the amount of time the system is exposed to the damager is important.

The word, severity, and phrase, severity level, are meant to be very general; neither is used here in a specific sense. The higher the severity level the more damage is likely to be done to a system in a given time or the more likely it is to fail. The only way of knowing whether a particular set of stresses and damagers produces a higher severity level is to know whether in fact the system is more likely to fail or is being damaged at a greater rate. There are circumstances, electrical contacts for example, where increasing the voltage or the current being carried may actually improve the performance. Yet voltage and current are ordinarily considered to be damagers; so that increasing the damager level does not always increase the severity level. There also are situations wherein increasing the temperature will improve the life of the equipment, especially if by so doing it is generally kept drier.

The literature does not often distinguish between a stress and a damager in this way, therefore the word 'stress' when it is used in the sense of damager will appear in single quotation marks. The word stress is so ingrained in much of the literature that at times it would be disconcerting to the reader to use the word damager in its place. For example, in step-'stress' testing.

2.6 Failure modes and mechanisms

A distinction is often made in the literature between a failure mode and a failure mechanism. Failure modes are the ways in which the element fails; the mechanism is the thing responsible in the element for the failure; but these are relative terms. For example, the failure mode for a computer may be some kind of incorrect calculation and the failure mechanism may be loss of memory. To the memory manufacturer, the failure mode would be the way the memory failed and the mechanism could be a core-driver failure. To the maker of core-drivers, the failure mechanism might be a transistor-open. To the transistor manufacturer the mechanism might be failure of the aluminum metallization pads, and so on down the line.

There is a good analogy here between strategy and tactics. Failure modes correspond to strategy, failure mechanisms to tactics; the Colonel's tactics may well be the Lieutenant's strategy. While the distinction between failure modes and failure mechanisms is sometimes worthwhile, it cannot be made in an absolute sense.

2.7 Wear out

There is some confusion in the literature about the meaning of "wear out". The term derives from mechanical wear which is often represented by a Gaussian distribution (usually there is a time transformation). The failure rate of the Gaussian distribution has the traditional bell-shaped curve, but the hazard rate of the Gaussian distribution is continuously increasing. In the so-called bathtub curve the hazard rate decreases at first, then stays constant, then increases (those curves which show the bell shape at the end of the bathtub curve confuse failure rate with hazard rate). An example of a decreasing hazard rate is given by a Weibull distribution with shape parameter less than 1. The only constant hazard rate function is the exponential. Examples of increasing hazard rate functions are the Gaussian and Weibull with a shape parameter greater than 1. The only legitimate definition of "wear out" that can be made in analogy to mechanical wear is that the hazard rate has begun to increase appreciably. Any other definition will lead to serious conceptual difficulties if not logical contradictions.

3. Programming the severity levels

3.0 The most familiar ways of programming the severity levels are constant-'stress' and step-'stress'. It should be emphasized here that the term severity-level is quite general. It does not necessarily imply a constant value of a particular environmental factor but may involve rapidly changing amplitudes of various factors according to a prescribed pattern. At a given severity level the distributions involved would be stationary, ie, the parameters used to describe the various distributions (whether of amplitudes, duty cycles, etc.) would be the same irrespective of the particular time at which they were measured. The averaging time must be short compared to the failure time. For example, one severity level for an environmental check might be transfer every 10 seconds from ice water ($0^{\circ}C$) to hot water ($95^{\circ}C$), where life is expected to be several hundreds of cycles. An increase in severity level might be the alternation in the same period from a dry-ice alcohol mixture ($-80^{\circ}C$) to a hot liquid bath ($150^{\circ}C$) where again life is expected to be at least several hundred cycles, but shorter than for the first test.

Increasing the severity level on any of these tests means increasing the amplitudes, duty cycles, etc. of the factors involved in the severity level so that the item is more likely to fail. It should be remembered that severity level is in general a multi-dimensional (-component) quantity (a vector). Consider for example a severity level composed of vibration, high temperature, and low voltage. Offhand it would be difficult to know what a simultaneous decrease in voltage, increase in temperature, and decrease in vibrational level would do to the severity level without actually running the experiment. Presumably before any comprehensive tests are planned, such details will have been worked out.

The statistical design of the tests is important, although it is usually not complicated. Before any statistical design can be effected, a conceptual model of the failure behavior must be created. The model will usually have fairly standard parts and assumptions -- adapted from those used often by statisticians. This is fine as long as they don't do too much violence to the engineer's ideas of what will or won't happen. It helps if the analysis accuracy does not require absolute adherence to the model, but rather allows plenty of leeway. The engineer must not abdicate his responsibility in this area to a statistician. He should use the statistician as a consultant so that the outcome of the test can best serve the engineer's own needs. He must make his own needs as explicit as possible to the statistician and must make his own compromises between tractability of analysis and simple mindedness of the assumptions on which that analysis is based.

3.1 Constant-'stress' level

This is the traditional type of test wherein the severity level remains constant throughout the life of the items on test. Several items are usually put on test at the same severity level simultaneously and the test stopped when some fraction of the original sample has failed. For reliability prediction purposes the early fraction that fails is most important because only the short-lived items are going to seriously affect the reliability. For engineering improvement purposes the fraction that is very long-lived may be important as an example of a construction which did in fact prove quite reliable.

It is customary to run tests at several severity levels and to plot a curve (showing some measure of goodness vs the measure of severity level) which is faired through the resulting points. The measure of goodness may be failure rate, time to failure, etc. The measure of severity level where there is only one dimension is usually easy; some function of the parameter used to describe that dimension is plotted. As is traditional with engineering, one hopes to choose the coordinate axes so that the damager vs goodness line is predicted to be straight. The same thing can be done where more than one dimension of the severity level exists but only one damager is being changed. If more than one damager is being changed, then it is up to the engineer to either

1) find some scalar which will measure the overall severity level; or
2) plot each one of the dimensions of the severity level. This immediately creates a problem for graphical presentation but the analytic continuations can easily be written down in their generality.

Most theories of cumulative damage have constant-'stress' tests as their reference.

As an example, consider the capacitor life tests described in #L-078, ---, fixed voltage (400 Vdc) with temperature as the 'stress'.[1]

No. of capacitors at each severity level:	100
No. of severity levels:	4
Fixed calendar time for each level:	2688 hr

Test Results

Temperature (°C)	No. of Failures
25	1
70	0
125	4
145	12

The references give no analysis, only the data. Therefore, for the model, suppose that the hazard rate is a constant at each temperature and that it follows the Arrhenius equation as a function of temperature. This is the situation analyzed in Appendix C. We have picked an available method of analysis that we hope doesn't do too much violence to reality. The results are given below.

	Point Estimate	Estimated Standard Deviation	Range for ±2 Std. Dev.	Units
Activation energy	0.363	0.133	0.096 ↔ 0.620	eV
Ln (hazard rate at 25°C)	-14.272	1.380	-11.512 ↔ -17.032	-
Hazard rate at 25°C	0.633	$\overset{\times}{\div}$ 4.0	.04 ↔ 10	$1/10^6$ hr

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[1] The complete test was a matrix test for both voltage and temperature. A subset of that experiment is discussed here. For the #L numbers, see the list at the back of this report.

It is obvious that the uncertainties in the results are much greater than are ordinarily assumed. Furthermore, these are the uncertainties which were calculated assuming that the model was accurate. It does not deal at all with the possibility that the hazard rate is not constant with time, nor with the possibility of non-Arrhenius behavior of the hazard rate. But, given only the information we have, it would be virtually impossible to do any better.

The important design considerations are fixing the following items:

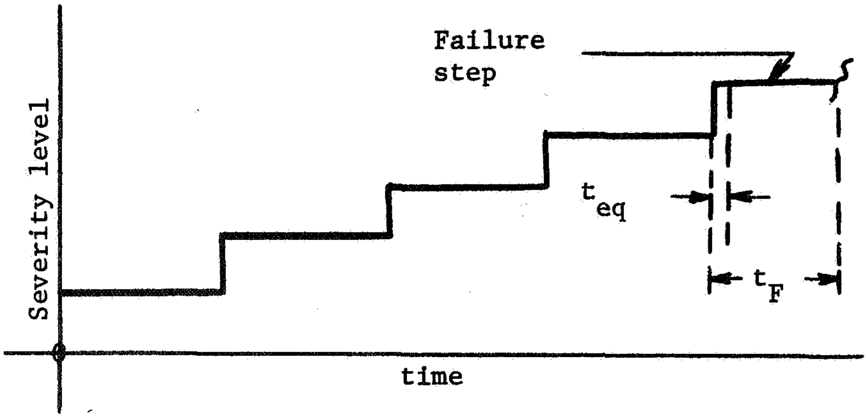
1) Number of severity levels,
2) Spacing of the severity levels,
3) Criteria for stopping the test,
4) Number of specimens at each level,
5) Kinds of severity levels
    a) Time behavior of damagers
    b) Number of damagers
6) Severity of each level
    a) Level of each damager
    b) Use of a scalar or vector to describe the level.

This will usually be largely determined by the resources at hand rather than the desired accuracy of results. This is so because one usually runs out of resources long before he achieves the accuracy he would have liked and thought he "needed." When this is not the case, a model must be assumed in order to get optimum values for any of the above. The criteria for optimality will depend on the choice of model and the kind of information needed. A good statistician will be invaluable in <u>helping</u> to make the tradeoff decisions.

3.2 Step-'stress'

The term step-'stress' as used in the literature is ambiguous. It is convenient to classify step-'stressing' into three categories: large, medium and small steps of damager.

Large steps--the steps are presumed high enough and long enough so that $t_F >> t_{eq}$.



t_F is the time to Failure on the Failure step.

t_{eq} is the equivalent time it would have taken on the Failure step to accumulate the damage that was actually accumulated at all the lower steps.

Failure step is the severity level at which failure occurs (it may be different for different specimens).

An easier but less specific statement is that the cumulative damage up to the last step is negligible.

Small steps--in this case the steps are small enought so that in the analysis one can presume with negligible error that the severity level is steadily increasing. This is then just the progressive-'stress' case (Sec. 3.3).

Medium steps--the assumptions for neither small nor large steps are valid. The cumulative damage at previous steps must be taken into account but the steps are not small enough that the severity level can be considered continuously increasing.

In order to be able to refer reasonably to these three cases the following terminology is used: large/step-'stress', medium/step-'stress', and small/step-'stress'. The size designations are not absolute but are relative to the kind of analysis that must be performed.

Large/step-'stress' tests are analyzed as if they were constant-'stress' tests being run at the severity level of the Failure step. Parts which are very expensive or otherwise difficult to acquire or test are often treated in this way. Often a sample of only one is used. It is wise to consider the results as ballpark figures since the necessary assumption of negligibility of previous steps is likely to be in error. Preliminary tests are very often run in this way to be followed by a more comprehensive set of tests later.

Small/step-'stressing' is analyzed the same as progressive-'stressing', and in fact by definition there is really no distinction between them. Whether in actual practice the value of a severity level jumps in small but nonzero increments or rises smoothly is a matter of resolution of measuring instruments or of pencil lines on graph paper. In many cases there will be a large economic advantage to choosing either very small step increments or a nominally continuously increasing procedure. As an example, if extremely accurate voltage steps are desired, a stepping switch might be used with a voltage divider; otherwise a slow motor might be used to turn a multi-turn potentiometer.

The only difference in analysis between medium/step-'stressing' and progressive-'stressing' is the summation sign's being required in the former and an integral sign in the latter. Caution may call for increasing the measure of severity level in such a way that this summation or integration is very tractable. Discretion is often the better part of valor and a short period of forethought and preparation may overwhelmingly pay for itself by replacing the need for a complicated digital computer analysis with one which can be done by hand via the evaluation of a simple equation. As an example, consider a situation wherein the Arrhenius equation is presumed, temperature is being increased, and linear cumulative damage is assumed. If temperature itself is increased linearly[2], the summation will be intractable; if 1/T is increased linearly the equations are tractable; further, if $\exp\left(-\frac{E}{kT}\right)$ is increased linearly the analysis may be even more tractable.

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[2] Continuously or in equal steps. For details of the reasoning, see Appendix D.

Before medium/step-'stress' or small/step-'stress' tests can be compared with constant-'stress' tests some theory of cumulative damage must be assumed. In the area of metal fatigue for example there are many such theories of cumulative damage, but there are not many in electronics. Most engineers have used the old rule of thumb--when in doubt, chicken out--and they use the simple linear theory. This linear theory is discussed in Sec. 3.6.

For some kinds of elements the maximum useful severity level will be exceeded before the device fails. For example, on transistors which are thermally 'stressed' there are points where melting occurs and the transistor essentially ceases to be a transistor. There are other cases where the failure mode changes so drastically at some level that it is senseless to continue testing above that level.

The severity level is often not started at zero. Typical reasons are:

1. The damage rate is negligible until a certain level is reached.
2. The failure mode may be a function of damager level. Temperature is the best example, wherein "room temperature" is usually the most benign.
3. It is not convenient or possible to do so with the experimental equipment at hand.

The important design considerations are

1. The slope of the severity-level vs time curve, viz, the ratio of severity-level-increment to time-at-constant-severity-level.
2. The magnitude of the steps--both in a qualitative (large-medium-small) sense and quantitatively (exactly the amount of increment).
3. The severity level limits.
4. Initial severity levels.
5. See also the factors listed under constant 'stress' above (Sec. 3.1).

It is possible to change the slope and magnitude of the steps during the course of the tests--there is no law that says they have to be constant. As a matter of fact if the change in slope is monotonic with step number there will always be a transformation of time and/or severity-level measure such that the steps are equal. Tractability of analysis and ease of running the tests are often the governing factors. The severity level limits, which usually are where the device ceases to be its usual self, are an important limitation to step-'stressing'. When these limits are encountered before enough failures have occurred, then the slope must be decreased. It is quite possible under this condition to have to decrease the slope to the point that the tests "degenerate" into constant 'stress' tests.

In the literature it has been asserted that step-'stress' tests have the advantages that there are no immediate failures due to switch-on because the severity level is zero at the beginning and that there are no run-outs[3] because the severity level can go indefinitely high. Unfortunately the latter is not true if the severity limit is exceeded.

An example of this kind of stressing is given in #L-002 for mica capacitors.

3.3 Progressive'stress'

The problems and considerations associated with progressive-'stress' testing are essentially those of medium and small/step-'stress' tests. As mentioned in Sec. 3.0 there is no need to belabor the difference between small/step-'stressing' and progressive-'stressing'; the only difference between medium/step- and progressive-'stress' testing is in the tractability and form of the resulting analysis.

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[3] A run-out is the result of a test wherein time (or number of cycles) has run out and the test was stopped before failure occurs. It is a time truncated rather than failure truncated tests. There is often an implication that the failure mode being tested for would never occur.

3.4 Other programs

Some kinds of programs which are concerned with investigating cumulative damage theories may change the severity level only once during a test. For example, the initial part of one test may be at a high severity level and the remainder at a low severity level; the second test reverses the procedure. Not much work of this sort is done in electronics, but metallic fatigue is a field wherein these methods of programming have received considerable attention.

The term 'probe testing' has been used in the literature, but this testing is a special case of step- or progressive-'stressing' where the severity level is a vector with several dimensions (components).

While it is not often done in electronics, one test procedure is to record the actual severity levels on a particular element in the field and reproduce these in the laboratory. In some cases this approach fits the concept of a constant-'stress' test. (See Sec. 3.1.) There is no reason why the programming of the severity levels in an accelerated test cannot be anything which will add to the useful knowledge about the system.

3.5 Matrix testing

Matrix testing is a misleading phrase to one who has not run across it before. It does not refer to the kind of test being run but to the way in which the test is planned. It gets its name from the fact that the damager levels of two or more damagers at which tests are to be run are laid out often in a matrix form for easy viewing and understandability. Individually, each test is a constant-stress test.

If a statistician uses some of his detailed experimental designs, he will vary more than one parameter at a time, however, the test conditions may not fit in a simple matrix form. This is of no concern since the name "matrix" is not important except as a means of conveying the idea that more than one parameter is being changed.

The important design considerations are:

1. how many dimensions will be considered
2. for each dimension, the considerations under constant-'stress' apply (Sec. 3.1).

Rarely, if ever, is this kind of test done for qualitative purposes. So the method of analyzing the model is important and is an essential part of the experiment. Two books which can be helpful to engineers in designing and analyzing this kind of experiment are Refs. 1,2. Reference 1 describes and gives some experimental designs, while Ref 2 concerns least-squares analyses.[4] If enough is known about the process, statisticians can be of help in planning the experiment. You must know something about the variability of the process when you run it under nominally the same conditions (viz, how well does it repeat itself?). It helps to know this over the range of parameters of interest. In addition you must know the important parameters to control or measure, eg, if the humidity of a test chamber is important but unknown, and there are sporadic sources of water, you are in trouble and no statistician can get you out of it without pain and suffering. Very often one will wish to extrapolate[4] the results outside the region of the matrix and in this case Sec. 5 should be consulted.

If interpolation[4] only is desired there are four main ways of utilizing the data.

1) Use the equation from the conceptual model and evaluate the unknown parameters. If a technique such as least square is used, be careful about weighting of the various points. If the equation is at all tractable the model will usually be rather simple-minded.

2) Use a linear or second degree equation in a general form and calculate the unknown parameters (brute force method). The only reason for limiting the equation to second degree is that rarely does one have enough data to go any further, nor does the accuracy of the data that you do have warrant it. This equation is often called a surface.

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[4] For a detailed discussion of extrapolation vs interpolation, see Appendix E.

Appendix H gives some details of least-squares analyses, and includes references to the method of maximum likelihood.

3) Make contour[5] plots. These can be calculated from the equations in #1 or #2 or can be faired through the data points directly. Particular kinds of contour plots are sometimes called schmoo plots, presumably because of the resemblance of some of the contours to the schmoos of Lil' Abner fame.

4) Computer routines. Each computer routine fits some kind of model to the data (see methods 1,2 above) and prints out the results in a certain way. The distinguishing features are speed and comprehensiveness of analysis, and ignorance (usually) of the basic assumptions involved in it.

After having calculated the equation it is most wise to go back and evaluate the equation at each of the data points and estimate the error or uncertainty involved. It is also worthwhile deciding, either before or after the evaluation at the data points, whether the scatter is due to actual differences in the items or due to errors and uncertainties in the measurements. In the former case one would call the lines average lines and expect a reasonable degree of scatter about them. In the second case the lines would be called true curves. Even within the range of the data you must be careful that the equations do not predict foolish things. For example, the equation might predict negative hazard rates in some region (this has happened in the literature). Obviously if the uncertainties in the calculated parameters were known or if the deviations of the data points from the calculated points were known, such absurdities could be censored.

At the risk of repetition: If there is much scatter or uncertainty in the data, always estimate the uncertainties in the calculated parameters and/or calculate the deviations of the calculated curve from the data points. In this way you can avoid making a fool of yourself in print.

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[5] Contour plots are so named because of the direct analogy to elevation contours on a map. Assume that x,y is the plane of the paper and z is the direction perpendicular to it. Lines of $z = z_1$ = constant are drawn throughout the x,y. Each such line is called a contour and is usually labeled with its value of z_1.

3.6 Cumulative damage

In order to compare tests (or field experience) run under different severity-level programmings, some model of cumulative damage is necessary. No particular model is required, merely some model. In electronics there are very few theories of cumulative damage, regardless of the part, but in mechanical fatigue for example there are many models of cumulative damage. Most often such a model uses constant-'stress' tests as its basis. The most common conceptual model, in almost any field, for cumulative damage is the so-called linear model. It has one basic assumption, viz, the rate of doing damage is 1/MtF where MtF is the Median time to Failure [6,7]. The MtF is for the particular severity level at which damage is accumulating. There are several corollaries [8] to this assumption which are often (but improperly) stated as additional assumptions.

1) The rate of doing damage does not depend on the amount of damage already done.
2) The order in which the severity levels are applied makes no difference.

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[6] The median is the value above which half of the measurements lie and below which half of the measurements lie. In contrast to the arithmetic mean, it makes no difference to the median how large or small the measurements actually are in either group.

[7] The Median (ie, 50th percentile) is the conventional fraction to use. One could as easily use some other percentile, eg, 1% (1% have lives less than the given time). The percentile in the definition and in corollary 5 must agree, of course.

[8] Corollaries 1,2,4 are true because the damage rate depends only on MtF, not on time (for #1) nor on severity level order (for #2) nor on the value of MtF for some other severity level (for #4). Corollary 3 is true because total damage D is $D = \int_0^t \frac{dD}{d\tau}\, d\tau = \sum_i \left(\frac{dD}{dt}\right)_i \int_{\Delta t_i} d\tau = \sum_i \left(\frac{dD}{dt}\right)_i \Delta t_i$.

Corollary 5 is true since the median time to failure, at a given severity level is MtF, by hypothesis; the total (median) damage is damage-rate (1/MtF) times time (MtF) which is unity.

3) The total damage is the simple sum or integral of the damage done at each stress level.
4) The rates of doing damage are independent of each other for different severity levels.
5) The Median [7] endurance at constant severity level is unity.

With regard to Corollary #5, the actual endurance is $1 + \epsilon$, where ϵ is a random variable; its statistical properties depend on the programming of the severity levels, on the probability density functions of the times to failure at each severity level, and on the Percentage chosen in footnote 8. It it usually presumed that the calculated life is the Median (or the Percentage in footnote 8). An example of calculating the life of an element, when it is exposed to several levels of severity during its life, is shown in Appendix F.

The use of a cumulative damage model does not necessarily mean that the failure modes/mechanisms were the same at each severity level, although such a case may help the validity of the model.

The linear model of cumulative damage is generally regarded as a gross approximation. In some circumstances it consistently underestimates and in other circumstances it consistently overestimates the correct value. Regardless of these deficiencies it has the big engineering advantages of being tractable, easily remembered, and widely used. So, use the linear model unless you know of some other which is better. But, in your report, please state the arbitrariness of this assumption.

4. Thermal acceleration equations

4.0 Temperature is probably the most important damager for accelerated testing that we have. It has been used and analyzed a great deal in the past, and its continued use appears both easy and fruitful. The equations used in the literature to describe the accelerated behavior are a matter of some controversy. There are many experimental situations wherein temperature is changed, the results recorded at each experiment, then log (results) are plotted vs 1/kT (or against 1/T). This is often done because the conceptual model being used to describe the process suggests that the resulting line will be nearly straight (neglecting random variations). Many of these situations have nothing to do directly with the Arrhenius or Eyring equations although they probably all, including the Arrhenius and Eyring, have their roots in the Boltzmann distribution. For example, the product of the electron and hole concentrations in a semiconductor is given by

$$np = P(T) \times \exp(-E_g/kT)$$

where P(T) is a "polynomial" in T (perhaps containing fractional exponents) and E_g is the bandgap energy. There are thermodynamic equations which have been put in the form

$$y = \exp(-E/kT)$$

where E is some thermodynamic energy. One of the reasons this form is preferred is that it turns up in the rather tractable analysis for perfect gases. Therefore in other situations, some new generalized parameters may be defined by an equation of that form. The energies E and E_g above are not usually constant, but the variation of either with temperature is usually quite mild compared to the T in denominator. It happens to be convenient sometimes to split the E in the above equation into two parts, E_1 and E_2, such that $\exp(-E_1/kT)$ is a "polynomial" in T (fractional exponents allowed). The resulting equation is $y = P_1(T) \exp(-E_2/kT)$. Unless the data are quite accurate, much more so than usually found in engineering experiments, the variation due to $P_1(T)$ is completely swamped by the random variations measured in y. In some experiments in basic physics (eg, determining the bandgap energy of silicon) or in chemistry (eg, the hydrogen iodide decomposition into hydrogen and iodine) the results are accurate enough that it behooves one to get a reasonably accurate model for the "polynomial" in T. Then the y's can be corrected[1] and the nonstraightness of the resulting line will be due solely to the temperature dependence of the energy in the exponent. It is worth noting that the energy of the exponent is associated with a physical quantity only to within a few kT because many models neglect variations in energy of this amount. The variations are quite small, eg, at room temperature $kT \simeq 0.025\text{eV}$.

Other forms relating time and temperature have been used in chemistry and metallurgy (rarely in physics). In particular, a time-Temperature parameter (tTp) is introduced and the observed behavior is postulated to be expressible in terms of this tTp with no other time or Temperature dependence.

The reasonable success of the exp(-E/kT) equation has led many people to speculate on extensions of it to include damagers other than temperature. These extensions have been completely arbitrary and should not be imbued with any mystical sense of theoretical soundness.

4.1 Arrhenius

This is certainly the classic example for temperature dependence of specific reaction rates and can be written [2,3]

$$rr = A \exp(-E/kT).$$

While we do not have access to the personal thoughts of Arrhenius, the form of his equation was undoubtedly influenced by the thermodynamic forms mentioned in Sec. 4.0. The Arrhenius equation has enjoyed an appreciable amount of success for both interpolation and extrapolation.

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[1] Instead of plotting log y, plot log $[y/P_1(T)]$.

[2] Sometimes an R is used in place of the k. R is the universal gas constant; k is Boltzmann's constant. Chemists tend to use the former and physicists the latter, the difference being per mole or per molecule, respectively. When R is used, E is usually given in kilocalories per mole, whereas when k is used, E is usually given in electron volts per molecule. $1 \frac{\text{kcal}}{\text{mole}} = .043363 \frac{\text{eV}}{\text{molecule}}$, $23.0609 \frac{\text{kcal}}{\text{mole}} = 1 \frac{\text{eV}}{\text{molecule}}$. Very often the per molecule or per mole is implied rather than being stated explicitly.

[3] A is often called the frequency factor because the earliest reactions considered were of the first order. This name does not apply to reactions of other orders.

The Arrhenius equation is often written in an approximate form when the temperature excursions are small, as

$$rr_1/rr_2 = \exp(-E/kT_0 \times \Delta T/T_0),$$

where T_0 is the nominal temperature of the reaction. The uncertainties in the experimental data in many practical situations will swamp out the error in the approximation. A very common form of this approximation is the statement that specific reaction rates will double for every 10°C rise in temperature. If T is given, and if $\Delta T = 10^\circ K$ and $rr_1/rr_2 = \frac{1}{2}$, then E is determined by the equation. For example, if T_0 is in the range 0 to 100°C, E will be 0.6 ± 0.1 eV. Thus for practical purposes, doubling of rate per 10°C is equivalent to a 0.6 eV activation energy (which is close to that for many chemical reactions).

If the results of an engineering investigation show that the Arrhenius behavior is not followed, all that such results mean are that the system is obviously behaving in some other fashion. The results do not mean anything is right or wrong, but simply that the simple-minded conceptual model being used is inadequate.

Since its birth over 75 years ago, the Arrhenius equation has undergone modifications in endeavors to make it more widely applicable. These modifications are of little if any concern in accelerated testing; they are discussed in texts and articles on physical chemistry.

4.2 Eyring[4]

The Eyring equation, or as it is more often known in physical chemistry, the equation for absolute reaction rates, seems to have assumed an undue God-like image in some of the reliability-physics/accelerated-testing literature. The specific reaction rate may be written as

$$rr = \frac{\kappa kT}{h} \exp\left(\frac{-\Delta G^\dagger}{kT}\right)$$

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[4] All the quotations in this section (Sec. 4.2)are from Ref. 3--an excellent short (2½ page) reference by Eyring on absolute reaction rates.

where $\Delta G^{\dagger}$ is the Gibbs free energy of the activated complex,

κ is a transmission coefficient and is usually virtually unity,

h is Planck's constant, and

$\dagger$ is a superscript which indicates the activated complex (often a $\ddagger$ is used).

"It should be clearly noted that the equation has been developed for an elementary reaction and that it should be applied only to such a reaction."[4] "The absolute reaction rate theory... has been applied with success to a wide range of solid, liquid, and vapor phase reactions. It is equally useful in considering the rates of very rapid reactions which may occur in a flame, and the rates of those reactions which under ordinary conditions require geologic ages."[4]

The big reason this equation "always" applies is given under Sec. 2.1 of models: some of the factors and concepts involved in this equation are defined by equations which go to make up this one. This does not diminish the value of the equation in any way; it just puts it in perspective.

Now since $\Delta G^{\dagger} = \Delta H^{\dagger} - T\Delta S^{\dagger}$ where $H^{\dagger}$ and $S^{\dagger}$ are enthalpy and entropy of the activated complex respectively (the $\dagger$ denotes the activated complex), the equation can be put in the following form

$$rr = \frac{kT}{h} \exp\left(\frac{\Delta S^{\dagger}}{k}\right) \exp\left(\frac{- H^{\dagger}}{kT}\right) .$$

The $\Delta H^{\dagger}$ is closely associated with the activation energy and is equal to it within an uncertainty of a few kT (depending on the exact conceptual model chosen for the reaction kinetics). It is the term $\exp(\Delta S^{\dagger}/k)$ that gives the trouble. A potential energy surface can be introduced and if there are not too many dimensions (say only one or two), and the system is extremely simple, and you are lucky, this surface can be obtained from quantum mechanical considerations. Actually, "For all but the simplest systems this is not feasible. There are also semiempirical methods for the calculation of these potential energy surfaces, but these do not generally give sufficiently accurate surfaces for practical use in predicting kinetic data. In fact, for all but the very simplest reactions one examines the nature of the activated complex from experimental kinetic data." [4]

Electronic components are complex engineering systems from the point of view of theoretical chemistry/physics and for practical purposes, use of absolute reaction rate theory will offer little if anything over the Arrhenius equation. One of the biggest obstacles to its use is the tremendous scatter in the failure rate data. Another is that the specific reaction rate is not observed, but some complicated function of it is. By the time one is discussing failure rates, he is a long, long way from a specific reaction rate.

4.3 Time-Temperature parameter

The behavior of many materials and substances is affected by being exposed to higher temperatures and the behavior is influenced by both the temperature and the amount of time at that temperature. Thus to accomplish a given change, there is often a trade-off between time and temperature. This is true for activities as diverse as cooking meat and creep-rupture of steel. The Arrhenius equation has long been a favorite for the specific reaction rate constant in chemical reactions; a similar form is often used for the temperature dependence of the rate of change of a parameter (p) with respect to time. In this latter form one can write

$$\frac{dp}{dt} = A \exp(-\frac{E}{kT})$$

where A and E are constants, ie, they are independent of

a) time,
b) temperature,
c) the parameter under consideration.

It is #c above which forces dp/dt to be this special function of the parameter, p, rather than just an arbitrary function.

For example, if a chemical reaction is a second order one for component a then $\frac{d(a)}{dt} = B(a)^2$ where (a) is the concentration of a. The following manipulations are easily performed:

$$B = \frac{1}{(a)^2} \frac{d(a)}{dt} = \frac{d[-1/(a)]}{dt} = \frac{dp}{dt},$$

where $p = -1/(a)$. Thus we have found a parameter, p, such that $\frac{dp}{dt} = B = A \exp(-\frac{E}{kT})$.

The equation $\frac{dp}{dt} = A \exp(-\frac{E}{kT})$ is easily integrated resulting in

$$\Delta p = At \exp(-\frac{E}{kT})$$

where Δp is the change in p which occurs during the time from 0 to t. Some algebraic manipulation results in the equation

$$T \ln At = T \ln \Delta p + E/k.$$

If Δp can be chosen so that its value is 1, then the above equation reduces to

$$T \ln At_1 = T \ln (t_1/t_0) = E/k + T \ln(1) = E/k$$

where t_1 is the time interval for $\Delta p = 1$, and $t_0 = 1/A$.

The time-Temperature parameter (tTp) is defined by

$$tTp = T \ln (t_1/t_0)$$

and is a constant (although it is related to the activation energy).

It should be noted that this derivation is valid only when Δp can be assigned the value 1! This clearly eliminates any consideration of using the tTp for a) cumulative damage, or b) plotting the value of any continuously changing parameter. This is so because once the value of 1 has been assigned to Δp for a particular amount of change, it cannot be reassigned for the same situation. Most of the derivations in the literature do not include the term Δp, but rather, implicitly assume that it is 1; this has led to some misunderstandings. Clearly if Δp is allowed to be a variable, then to derive the tTp from the Arrhenius is only possible with a Procrustean approach to algebra.

Thus, while the Arrhenius equation is quite suitable for theories of cumulative damage, the time-Temperature parameter has additional assumptions involved in it and is absolutely not suitable for theories of cumulative damage when the process is presumed to follow the Arrhenius law.

In the field of metals, the tTp is often called the Larson-Miller parameter. It was presented by these two authors in #L-079.

Another difficulty with the use of the tTp is the compression of the time scale. In many situations the constant t_0 is taken to be on the order of 10^{-15} hr, so that for 1 hr $< t_1 <$ 1000 hr, $15 < \log(t_1/t_0) < 12$. This range of times includes most accelerated test times for electronics. It can be seen that variations in failure time up to a factor of 3 will produce a change in the tTp of only a few percent. Thus compression of the time scale is severe, and discrepancies in the data are covered up whether by intention or not.

There is certainly nothing wrong with trying to fit the results of an accelerated life test of an electronic component with a tTp. The constant t_0 can be considered adjustable to give the best fit to the data. Just remember that time and Temperature can enter in no other way than through the tTp.

4.4 Non-valid extensions

As mentioned in Sec. 4.0 there have been extensions of the equation for absolute reaction rate (Eyring) which have been termed "generalized Eyring equations". They involve an exponential term in which two arbitrary constants and an arbitrary function of the measure of 'stress' are introduced.

The name, Eyring, applied to this equation should not mislead anyone into thinking that he and the other eminient physical chemists who developed the theory of absolute reaction rates are responsible for it. The equation itself is obviously the most gross empiricism, which while not bad in itself, takes the aura of primacy away from it.

4.5 What parameter is accelerated?

Very often in the electronics literature the life of an element is considered to have a certain behavior, eg, to have Arrhenius acceleration; but the exact meaning to be associated with this statement is not clear. If the life is a random variable (and it virtually always is) it is difficult to know what is meant by the phrase: the life follows a certain law. It is much more meaningful to assert that a particular parameter in the life distribution follows that law. For example, if the hazard rate is constant, the life distribution has a single parameter (λ), and it can be asserted that λ has the Arrhenius behavior. Other one-parameter distributions could be treated similarly.

If the life distribution has more than one parameter, eg, the Weibull[5] distribution, then it makes no sense at all to assert that the life follows the Arrhenius acceleration formula. Rather one must assert that one (or both) of the parameters in the distribution follows the Arrhenius formula. It is commonly (and implicitly) assumed that the reciprocal of the location parameter has the Arrhenius form and that the shape parameter remains constant. If in fact, the shape parameter remains constant, a very simple time transformation ($\tau = t^{\beta}$, $\lambda = \alpha^{-\beta}$) will convert the Weibull distribution to the exponential, and there is no need to treat the Weibull as a separate case. If the shape parameter does not stay constant, there are serious difficulties in interpreting the data unless the model includes a specific type of temperature behavior for both the location and shape parameters. In the Normal distribution, which also has two parameters, a similar problem arises, viz, separate

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[5] Weibull cumulative distribution: $R = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$; α is the location parameter, β is the shape parameter.

equations for temperature-behavior must be assumed for each of the parameters (mean and variance) in order to fit the data to the model.

If three or more parameters are used to fit the data, either in a single equation or by using a simple equation for each segment of the data, trying to decide upon a suitable temperature behavior for each may be virtually impossible.

You must always ask yourself the question: This is a thermal acceleration equation for what parameters?

4.6 Statistical estimation

There has been no quite satisfactory method in the reliability literature for estimating the parameters of the Arrhenius equation directly from a set of life data. A desirable way is actually to use the data to estimate the Arrhenius parameters directly.

Whenever the parameters of a model are estimated from the data, always estimate the uncertainty in the parameter estimates. Calculating machines and computers usually give a false sense of precision to point estimates of parameters. An estimate of the uncertainties can properly shatter this false sense. (See the example in Sec. 3.1, p. 16.)

Such a technique is shown in Appendix C. It gives the maximum likelihood solution for the parameters and for estimates of their variances.

If a least-squares analysis is used to fit the data points to a temperature model, attention must always be paid to the weighting of the data points in terms of their estimated accuracy. The weight given to any point is proportional to the reciprocal of the variance at that position. Even though least-squares is a legitimate technique, regardless of the probability distributions of the data, it has severe engineering limitations during interpretations of results, if those distributions are highly skewed.

Some authors have cautioned against transformation of the variables because of the effect on the weight of the points. One can transform the variables any time if he changes the weighting of the points with every transformation of the dependent variable. The weighting does not change at all with transformations of the independent variable. The help of a competent statistician will be worthwhile if the estimations are at all critical, eg, in meeting a specification.

5. Extrapolation

5.0 Just as everyone uses accelerated testing and will continue to use it regardless of the judgements passed on it and irrespective of its limitations, everyone will continue to extrapolate from the data regardless of the admonitions against and the dangers befalling extrapolation. It is not the purpose of this section to proscribe extrapolation but to show what uncertainties exist when it is done. It is presumed that some reasonable equation derived from a model of the process exists. Curves which are fit to data points by brute force with a series, such as a power series or orthogonal polynomials, are never[1] to be extrapolated. Those formulas are for interpolation only; they usually behave very wildly outside the data interval.[2]

If the data have been fit by least-squares (or some other criteria for goodness) or if a series with enough adjustable coefficients to fit the data exactly has been used, the caution is the same -- the extrapolated curve will not be a smooth extrapolation of the data points nor is it intended to be.[2] This is not an ivory tower proscription but a very realistic one.

5.1 Accurate model

If the model is accurate outside the range of the data, then the problem of the uncertainty in the extrapolation is statistical in nature. A statistician may be able to give help on the design of the original experiment to make the estimate of the extrapolated value as accurate as possible. Providing for making an accurate extrapolation is not necessarily the same as evaluating the parameters in the model as accurately as possible.

Virtually always in engineering, the data are transformed so that the resulting curve is a straight line; so only a straight line is considered in the following discussion. The principles are applicable to more complicated

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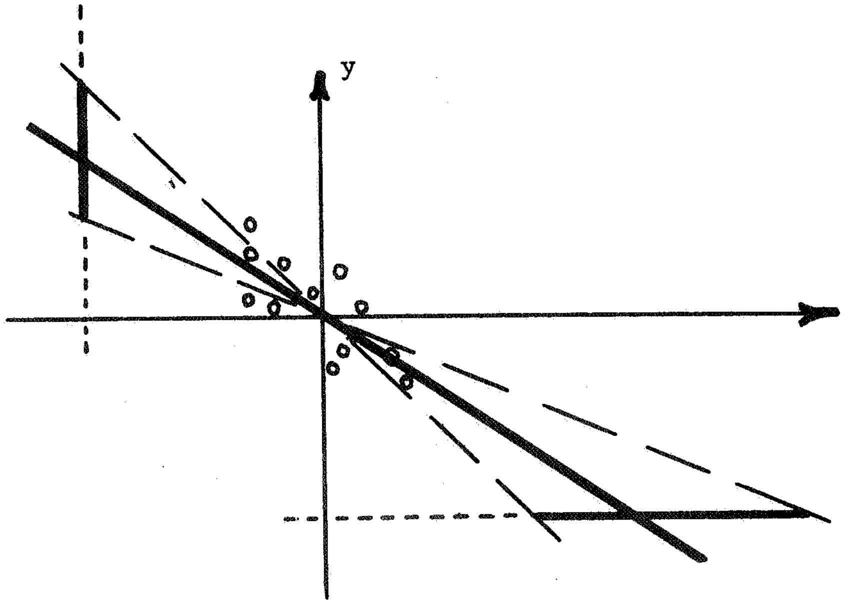
[1] There is, of course, the rare exception when the series is known to be accurate, even outside the range of the data.

[2] See the example in Appendix G if you are not familiar with this kind of behavior. A power series which stops at the linear term, cannot, by itself, get too wild. The more terms there are, the quicker the series can get wild--outside the interval of calculated fit.

curves however. Consider that the origin is at the "center of gravity" of the data points[3]. The straight line will be of the form $y = mx + b$ where, except for uncertainty, b is zero. In virtually all situations the error in extrapolating due to the uncertainty in b is negligible. The uncertainty in the slope m is what causes the trouble as is shown in the figure. The heavy line is the best line calculated by whatever means are desired. The dashed lines are the loci of confidence points about that line for extrapolation purposes. In the lower right of the figure[4] the uncertainty in x for a given value of y is shown as a solid heavy line. In the upper left the uncertainty in y for a given value of x is similarly shown. The details of calculating these intervals are included in many computer programs and are available in some statistics texts. If extrapolations are made very far, and they usually are, the uncertainty can be an appreciable fraction of the value. For example; where log time scales are used, uncertainties in time of factors of 10 → 100 are not unknown. These are very real uncertainties;



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[3] If the points are weighted in the analysis, the origin will be the weighted center of gravity.

[4] The exact interpretation and method of calculation of this interval are sometimes a subject of controversy, but, roughly at least, the illustration gives an idea of the difficulty. The objections arise because of the "reversal" of the variables with which the randomness is associated.

within the confidence limits stated you don't know where a point lies, and giving point estimates can be extremely misleading to the reader. Remember that this discussion presumes that the model accurately describes the behavior in the region of extrapolation. Models are often known to have a very restricted region of applicability; certainly this region should be included in any equations written down so that the limitations are kept firmly in view.

The sample calculation in Sec. 3.1 (p. 16) gives an example of this difficulty in extrapolation. Reference 2 discusses least-squares solutions in some detail and gives formulas for calculating the uncertainties involved. Appendix H gives the details when the curve to be fitted is a straight line. There are too many different circumstances to cover all of them in this report.

5.2 Unknown model

If the behavior in the region of extrapolation is not known to follow a particular model, or if, as usual, one is not sure whether or not the behavior follows the model in the region of interest, then it is often possible to hypothesize several models and to extrapolate according to each. If the decision you make on the basis of the extrapolation is extremely sensitive to the model which has been assumed, then you are in trouble. If the decision you make on the basis of the extrapolation is not very sensitive to the model, it is generally assumed to be safe to go ahead. Fortunately, very often the latter is the situation. No one really cares what the exact prediction of life of a component or a part is; all he really cares about is whether it is long enough. This is why many acceleration and extrapolation techniques are successful--the parts are very good, so good in fact that they transcend the limitations of the analysis.

In most engineering situations you have to work in regions where decisions are not clearcut and there just aren't enough data. Generally speaking if you are in a satisfactory region, someone wants to redesign the system and put you in a questionable one; this is a consequence of getting the most for the least. Under these trying circumstances, this section can be used only as a guide, but the idea of sensitivity to the exact model is very useful and can give the engineer more engineering confidence in his decision. In this kind of situation you must beware of the statistician's use of the word confidence, since in that use it is a very technical term and certainly does not mean engineering confidence. You can easily have one without the other. It is engineering confidence in a decision that an engineer wants--not statistical confidence per se.

6. Summary, comparison, and evaluation of procedures for accelerated testing.

6.0 The important models and concepts involved in accelerated testing have been explained in the previous sections. This section contains a summary of each of the various approaches used in accelerated testing; the comparison of the test designs, testing methods, mathematical models, and test programs; and final conclusions on the extent of success and applicability for each approach. Where it is appropriate, some of the discussion has been deferred for the following four sections which consider each component separately. The approaches to accelerated testing can be broken down in two convenient ways, one is with respect to purpose and the other is with respect to the kind of test. Each kind of test is then discussed with respect to design, method, and program. An important consideration when developing models for the probability of a given life for a component is in what way a measure of the severity level of the test or operation comes into the model. With the constant hazard rate hypothesis there is little difficulty, but with more complicated models it is easy to get into trouble or to be unnecessarily restrictive.

6.1 Purposes

For this discussion, accelerated testing is divided into four classes: exploration, improvement, screening, and prediction. Exploration covers early tests which are run for the purpose of accumulating general experience and is not discussed in detail. Rarely are such tests reported in the literature.

A big reason for accelerated testing is to compare product or process changes for the purpose of improving and optimizing them. The major assumption that is made, and it is important, is that the qualities or goodness being measured will keep their relative ranking regardless of the degree of acceleration. One way to check on this assumption is to see if the failure modes have changed because of the acceleration (Sec. 2.6 discusses the difficulties in making this decision). A few such tests have been reported in the literature. Generally, the detail of reporting is not sufficient to know how careful the investigators were, but most of the cases are reported as if they were done well (which is to be expected). Another way of improving the product via accelerated tests is to increase the severity level enough, so that failures are generated in a reasonable time. These failures are analyzed, physically and by mathematical models, to see if they could occur in the field. If they could, changes are made to eliminate the failure mechanism (taking care, of course, not to generate other worse ones). Some failure modes/mechanisms discovered in this way may not be detrimental in the field, but get in the way of a good burn-in, or mask other failure mechanisms during accelerated testing, so they are eliminated for that reason. The reports of this kind of accelerated testing are uniformly reasonable and good. It is a difficult thing to go wrong on--which makes it one of the most powerful reasons for using accelerated testing. In the Summary Charts for each component (Sections 7-10), exploration and improvement are called qualitative applications. The remaining two applications are called quantitative.

Many screening tests are run at high severity levels, both to make them more efficient in finding weak devices and to shorten the test time. Such burn-in screens are not covered in detail in this report because they do not represent a problem area in interpreting accelerated testing. This region, also, tends to have reports in the literature which are difficult to criticize.

The largest controversial purpose for accelerated testing is to make predictions about the behavior of the product at usual operating conditions. Extrapolation is then necessary (see also Sec 5) and the situation becomes more difficult for two reasons: 1) The results depend much more heavily on the assumptions and 2) the assumptions are much less sure. The most common criticism of papers which report predictions is that they do not discuss these two difficulties enough. It is hard to say how much success that the approaches for prediction have achieved since the true answers are rarely known. But predictions are often made and, naturally, virtually all of the papers appearing in the literature report success (or at least do their best to put on a good front). It is likewise difficult to say what the extent of applicability of this kind of extrapolation is, for the same reasons. When extrapolation is used it is extremely important that the model be hypothesized first, the concepts clearly defined, the analysis well worked out, and the uncalculatable risks clearly stated. Then one should always calculate the uncertainties involved under the assumption that his model is correct. He may even wish to try several such models and see in what way his course of action is influenced by the choice of model.

In general the approaches reported in the literature are quite applicable and can give good results. The poor papers, which are not infrequent, usually run into trouble on a poor inconsistent set of assumptions, incorrect analysis, and/or no calculations of uncertainties in the answers. All of these reinforce a false sense of accuracy.

6.2 Kinds of approaches

There are three basic approaches to accelerated testing, not all of which are mutually exclusive, they are matrix test, constant-stress test, and step-stress test. Very seldom does one see anything more complicated than these reported in the literature, eg, random stresses are rarely reported as being used for accelerated testing. Each of these approaches has been explained in earlier sections.

Constant-stress tests are the old standby and are virtually always applicable. The results are easily analyzed without too complicated a model and in fact one can do nonparametric interpolation, eg, for fraction survival curves. Results from these tests are used for analysis of designs and enjoy considerable success in this role. (See the example in Appendix F.) Difficulties do arise, usually from inadequate data, when one tries to hypothesize distributions for the failure behavior at each stress and to show how the parameters of these distributions are a function of stress. The more common assumptions are logNormal or Weibull with time, with one or both parameters changing as a function of stress. The problem involved in fitting the data to a model is that the ability to discriminate between this model and some other model is rather poor, because the data tend to have much scatter and to be rather sparse. Extrapolations into low probability tail regions are frequent and ill advised.

Matrix tests are often a sign that a statistician has been associated with the project. If he and the engineer have properly shared their responsibilities, excellent results can be returned for the resources expended.

It is most important that a model be explicitly recognized by the engineer (in addition to the statistician) and that he understand all of the assumptions involved in the statistical analysis which will be made. It is up to the engineer to make a final decision on their adequacy. Very often the results of such tests are fitted by a quadratic surface; if so, watch out for the dangers mentioned in Sec. 5. It is advisable, if it is economically feasible, to have enough replication and to have maximum completeness of the factorial design, so that the assumptions can be checked with regard to the constancy of the variance and the lack of interactions. Matrix tests have achieved success for many electronic components and are always applicable. One should virtually always consult a statistician when using a matrix test since his advice may easily pay for itself. The exact design of the experiment is insensitive to the amount of acceleration of the test and thus is not covered in this report. In laying out the matrix, especially, a statistician can give invaluable help in deciding at what points data should be taken. The exact experimental design will depend on the particular quantities one wishes to estimate from the data, what it is about the test one wishes to optimize, and what assumptions one is willing to make about the behavior of the system.

Occasionally in the course of exploratory work something similar to a matrix test will be run. In that case the engineer can do as he pleases about consulting a statistician. If one is consulted it would be wise to emphasize to him the exploratory nature of the experiments and to ask help in determining how much replication to use and where to put the points to get the most information about the process. Replication and the order in which tests are run can be most important. For example in a semiconductor furnace the time sequencing of runs can be very important due to build-up on the walls of the furnace tube.

Step-stress tests are often used for qualitative purposes, in which case no formal model is required. It is not even necessary to be concerned with the question of cumulative damage and its effect on the results. The applicability and success of this approach for the qualitative purpose of planning more refined tests, or just for exploratory purposes--to find out what ball park the game is being played in--are considerable. Step-stressing is economical of specimens, gives useful results, and can be as rapid as desired. See Sec. 3.2 (p. 17) for a detailed discussion of the concepts. Step-stress tests are also used where extrapolation is desired, and in this region things become hazy. Some points in the literature are not clear, especially for example, the assertion that the stress at failure has a particular distribution. The applicability of cumulative damage does not appear to be considered, yet it is easy to infer that there was some earlier model which would predict such behavior. Often the extent of success of such an application seems more in spite of, than because of, the exact model chosen. Until much more analysis of the applicable theory is available be very careful about using step-stressing for quantitative extrapolation.

Step-stressing has been compared successfully with constant-stress tests. To do so requires some theory of cumulative damage as mentioned in Sec. 3. The only theory appearing so far in the electronics literature is the linear theory of cumulative damage and no unsuccessful applications have been reported. This of course is not to say that there were not any, or that the extent of success is always easy to judge. Some minor deviations from the linear theory have been reported for capacitors (in fact capacitors are about the only place that the theory of cumulative damage has been applied) and were used as a tool to explore inadequacies in the original models. The approach of using step-stress compared to constant-stress via a cumulative damage theory is quite applicable anytime.

As a rule of thumb on the applicability of each approach, remember that for eyeball results they are all good, the more quantitative and less eyeballish the more necessary a statistician.

6.3 Test designs, methods, and programs

On simple tests, where the engineer understands the models and methods of analysis, and where they are not critical anyway, there is no need to consult a statistician[1]. For other situations there will be give

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[1] Consulting a statistician can often be a simple phone call. It need not always involve elaborate expensive consulting sessions.

and take between the engineer and the statistician. Usually the engineer will want more than his resources can get. From there on in the engineer will be making tradeoffs (giving up some of his requirements, making less acceptable assumptions, etc.--tradedowns would be more descriptive). It helps if the engineer knows some of the language the statistician will use--Ref. 1 will be helpful here--so that he can carry on an intelligent conversation. If you don't understand--ask (as an engineer, you aren't getting paid to be an expert statistician).

A few important points are:

1) If possible, explicitly state the model which is being hypothesized, before the tests are run.

2) Know what kind of analysis of the results you expect to perform and how you will perform it.

3) Some tests are sequential in nature, viz, the conditions for the next test are determined by the results of the previous test. Often these kinds of tests will give more data in the region where it is desired but the analysis tends to be more difficult.

4) It is very unlikely that all of the assumptions required in the model will be fulfilled in the experiments. A statistician can assist in determining which ones are critical.

5) Some experiments are run not with any particular analysis in mind, but just for exploratory purposes. Running this kind sequentially can often save on the number of experiments at the expense of consuming more calendar time.

6) When comparing two products or processes--in order to make a decision to accept/reject one or the other--a figure of merit (FOM) is used (whether called by some other name or not). It is worthwhile knowing how sensitive the decision is to the chosen FOM. For example, one process may have a low mean but a very narrow spread while another process has a high mean and a large spread about it. If the FOM is chosen as the point estimate above which 50% of the population will lie, then the second process would be better; if it were the point above which 99% of the population would be expected to lie

then the first process might be better. Or as another example, one process may have much longer life and fewer defectives but the defectives are not very screenable. Whereas another process has very screenable failure modes but there are appreciably more defectives. It would be difficult to say that the choice of one FOM over another was right or wrong; but since it is important which one is chosen, it pays to put some thought into it.

Two traps for the unwary are a) running what seems to be a simple test without having considered what assumptions and analysis will be necessary and b) running a complicated, expensive, statistically designed test without having understood all the assumptions you implicitly made. Both result easily in stacks of unusable data.

A difficult decision to make is how to allocate resources between planning, running, and analyzing the results. Even if not explicit, the decision is implicitly made, since some allocation will occur. As a rule of thumb; if the fraction spent on the tests themselves is outside the range, say, 30% → 80%, be sure you have good reasons why.

These kinds of considerations are rarely discussed in the literature on accelerated testing; so it is usually impossible even to infer what was done.

If you are in doubt about where to begin on an accelerated test of a device, the following sketch will help.

1) Begin with step-stress tests. If specimens are relatively cheap, adjust large steps to give failure inside one working day. Then try 24-hr steps, with a rise in severity level at each step to give estimated failure in a working week. You can now plan more extensive step-stressing (these may be progressive-stress of course) or go to constant-stress tests. (See also Sec. 3.2, 3.3 for a discussion of the important points.)

2) At first, run a subset of the constant 'stress' tests, usually at the higher severity levels and with inexpensive-to-apply-'stresses'. These, too, will assist in finding out the information you will need to plan further tests. Then more complete tests can be planned and run.

3) If desired to run matrix tests, the tests in #2 above can be used to fill some of the cells. The cells need not all be run in parallel, but if not, be careful of any sequence effects--is there a past-history effect on the equipment, will there be personnel changes, will the time of year affect anything (eg, humidity), etc.? Sequence effects and other biases can be insidious--randomization helps sometimes.

4) Models for the behavior are created and modified all along the way. In the absence of good reasons otherwise, traditional models (eg, Arrhenius for temperature) are usually used.

6.4 Mathematical models for time to failure

The models most often used are shown in the Table. The Weibull has another common form in which $\alpha^{\beta} \to \alpha$; this latter has the disadvantage that α and t do not have the same units. The reliability, R, always decreases. The behavior of the hazard rate is listed for each distribution. The exponential and Weibull distributions can have an extra parameter added.

It is difficult to distinguish, from the data, between a logNormal and the Weibull, especially if there are less than about 10 points. The scatter in the data (due to random selection and due, perhaps, to neither model's being quite correct) will be too great in either case.

Often in the literature when one of these distributions does not fit the data well enough, the graph is segmented and a separate distribution is fit to each segment. Unless there are compelling physical reasons for doing so (these can be discovered before or after such segmentation and fitting), segmentation should be avoided (except during "playing with the data"). It is brute force fitting and suffers all the disadvantages thereof. Sometimes a somewhat more complicated, or even just different, distribution will fit the data adequately.

The mathematical models as related to severity level are discussed below in Sec 6.5.

6.5 Mathematical models vs severity levels

When life measurements are taken at a high severity-level and need to be transformed to another severity level (where no measurements have been taken) what kind of transformation should be used? There is no one right answer to this question -- several methods are possible which do not lead to logical contradictions. Some of them are listed below, they may be used together and may not be always different.

Reliability Distribution Table

Distribution	Reliability ($t > 0$)	Hazard Rate	Hazard Rate Behavior
exponential	$\exp(-\lambda t)$	λ	constant
exponential with guarantee period	$1, \quad t < t_0$ $\exp[-\lambda(t - t_0)], \; t > t_0$	0 λ	constant different constant[3]
Weibull	$\exp[-(t/\alpha)^{\beta}]$	$\frac{\beta}{\alpha}(t/\alpha)^{\beta-1}$	$\beta < 1$, decreasing[4] $\beta = 1$, constant $\beta > 1$, increasing
Weibull with guarantee period	$1 \quad , t < \gamma$ $\exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right], \; t > \gamma$	0 (same as Weibull)	constant (same as Weibull)[5]
Normal[1]	$\Phi\left(\frac{t-\mu}{\sigma}\right)$	$-\frac{\Phi'}{\Phi}$	increasing
log Normal[2]	$\Phi\left(\frac{\ln t - \mu^*}{\sigma^*}\right)$	(see Normal)	increasing

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[1] $\Phi(z) \equiv \frac{1}{\sqrt{2\pi}} \int_z^{\infty} \exp(-\tfrac{1}{2}t^2)\, dt, \quad \Phi'(z) = \frac{1}{\sqrt{2\pi}} \exp(-\tfrac{1}{2} z^2)$

[2] The *easiest* way to handle the log Normal is to convert to the Normal by the log transformation. This means that if $\tau = \ln t$, μ is average (τ) and σ^2 is variance (τ). If functions of t are desired, appropriate transformations can be made, eg, $\frac{d}{dt} \equiv \frac{1}{t}\frac{d}{d\tau} \equiv t\frac{d}{dt}$.

[3] Note that there will be an abrupt discontinuity in the hazard rate at $t = t_0$

[4] The hazard rate is not defined at $t = 0$.

[5] Note that there will be an abrupt discontinuity in hazard rate at $t = \gamma$, for $\beta \leq 1$.

1) Use a time transformation. A function of time is hypothesized and the parameters of that function are presumed to be a function of severity level. The reliability function may not be of the same functional form at each severity level. The origin of time should be preserved in the transformation to avoid logical contradictions. Examples of satisfactory transformations are $t \rightarrow at$, and $t \rightarrow t^2/t_0$, (a, t_0 are constants with time, but are functions of severity level).

2) Transform the hazard rate. The parameters of the function for hazard rate are presumed to be some function of severity level. Examples are $h = (V/V_0)^a$, $h = \exp(A-E/kT)$, where V_0, a, A, E, k are constants with time and severity-level, V is applied voltage, T is temperature.

3) Transform the parameters in the Reliability function (Probability of success). Examples are a) the location parameter in the Weibull distribution is a function of temperature, b) the mean of a Normal distribution is a function of dissipated power.

The models for damage rate are discussed under the individual components in Sec. 7-10 except for temperature; the temperature models are briefly compared here. For a more full discussion of these temperature models see Sec. 4.

The Arrhenius equation is most often used as a mathematical model for temperature behavior. It is always a good choice unless evidence exists to the contrary (eg, the failure mode may be known to change drastically at an intermediate temperature). Sometimes the data can be divided into parts (eg, on the basis of failure mode), so that each part has Arrhenius behavior. Exponential temperature behavior (eg, a doubling temperature) has often been used in lieu of the Arrhenius equation. Rarely will the data be able to distinguish between the two. The model which will fit into the calculations best should be used. The use of the time-Temperature-parameter for cumulative damage is wrong as mentioned earlier. It can, however, be used for a given event; it will be equivalent to, but more specialized than, the Arrhenius model.

Literature Summary -- Philosophical, Theoretical, General

#L	Philosophical Theoretical General	Review/ Tutorial Advance Art	Elementary Intermediate Advanced	Temperature Model	Other Models	General Nature or point being made
004	General		elem.		exp. for life	military equipment can be accelerated
006	Theor	Adv. Art	interm.			derating is not always useful
007	Theor.	Adv. Art	interm			stress strength model of failure is better than go/no go
008	Theor.	Adv. Art				need better life tests and data sheets for transistors.
010	Phil.	Tutorial	elem.			must get better data and models.
014	General	Tutorial	elem.		exp. voltage for cap.	be careful of accel. test results
016	Theor.	Adv. Art	interm.	Arrh.		cumulative damage
020	Theor.	Adv. Art	advanced		λ vs stress	find optimium test design, is λ larger than λ_0?
021	Theor.	Adv. Art	advanced		λ vs stress	find optimum test design, what is λ?
023	General	Review	interm.			failure analysis is important
024	General	Review	interm.			short term tests can replace long term ones
025	General	Review	elem			very general review paper - minor on accel. test
028	General	Review	interm			reviews step stress, const. stress, matrix test - no analysis
030	General	Tutorial	interm.	empirical	various	know stress vs life to calc. reliability

036	Theor.	Tutorial	interm.	Arrh.	various	Step-stress theory and cautions
037	Theor.	Tutorial	elem.		Stress-strength	use probability as stress-strength
041 047	Theor.	Tutorial	interm.			relative acceleration of failure modes -- caution
042	General	Review	interm.			accelerated burn-in is essential
043	Theor.	Adv. Art	interm			constant stress -- in parellel, use go/no-go results only
044	Theor.	Tutorial	advanced	Arrh.	general Eyring	
046	Theor.	Tutorial	interm.	Arrh.	log Normal for step stress	accelerated testing is necessary
048	General	Tutorial	interm.	Arrh.	general, Eyring	give state of art on accel. testing
049	General	Review	elem.	?	?	accel. testing is useful for finding failure modes
051	General	Tutorial	elem	Arrh.		brief & general
061	Theor.	Tutorial	inter.	Arrh.	several for extrapolation	just pick your model and extrapolate
064	Phil	Tutorial	interm		Gaussian	plan tests well
072	Theor.	Adv. Art	advanced	Arrh.	various	derive Arrhenius from Delbruch
073	Theor.	Adv. Art	advanced		exp.	stress-strength into reliability (time)
076	Theor.	Adv. Art	advanced		Weibull	if data fit Weibull, more info. than go/no-go
077	Phil.	Review	elem.	Arrh.	5th power	need good data, platitudinous
079	Theor.	Adv. Art	advanced	Arrh.		derive tTp
080	Electromechanical parts				various	matrix tests, potential models for extrapolating hazard rate
082	General	Tutorial	interm.		various	usual models -- shown and explained
085	Theor.	Adv. Art	interm.		stress-strength	if all pdf's vs stress are known for all parts -- can calculate reliability

The chart "Literature summary--Philosophical, Theoretical, General" summarizes the literature which deals with the general nature and philosophy of accelerated testing, or which develops some of the theory, ie, mathematical models.

7. Resistors

7.0 Resistors have the distinct advantage of being about the only electronic part for which the system state often has one dimension (component). Mechanical factors such as shock and vibration are usually treated on the basis of the simple stress-strength model (described in Sec. 2.2.1). The usual situations are to run either a proof test to see if the resistor can withstand a certain mechanical stress or actually to measure its strength. Very seldom indeed will one of these mechanical factors be part of the ambient in a matrix test. The composition of the material surrounding the resistor, such as salt spray or humidity, is usually left to acceptance or qualification tests spelled out in Mil Specs or other purchasing documents.

This leaves three factors for running a matrix test. The resistance of the resistor, the ambient temperature, and the power being dissipated in the resistor. Various modifications may include a cycling effect of power and/or temperature, but as described in Sec. 3.1 these are effectively constant severity-level tests. The temperature considered is very often the hot-spot temperature on the resistor; at other times it is just the ambient temperature. For some kinds of resistors under some conditions, the proportion of ambient vs power that goes to make up a given hot-spot temperature is important. Usually the effect of power differences can be treated as a perturbation on the hot spot temperature. Operating vs storage tests often give different results due to aggravation of different failure mechanisms. It is important to be aware of failure modes and mechanisms because these help in determining what kinds of damagers to apply during the test.

The definition of failure is important especially if the resistors change their resistance but slightly. There are examples in the literature wherein the definition of the parameter being monitored had to be changed after the test began, and where the uncertainties in measurement were an appreciable fraction of the changes taking place.

Extrapolation from accelerated conditions can be carried out reasonably well largely because (as mentioned in Sec. 5.2) the extrapolated failure rate will usually be small enough so that some uncertainty in the model for extrapolation is unimportant.

The chart "Literature Summary--Resistors" summarizes the literature on accelerated testing of resistors. The test design, methods, and programs were all reasonably satisfactory for purposes at hand as far as can be determined from the papers. The analyses were not uniformly good, and the specific reviews should be consulted for details.

There are no definitive methods for accelerated testing of resistors and subsequent extrapolation to operating conditions. Each case will depend on how much the engineer does know and suspect about the behavior of the resistors, what assumptions he is willing to make, what resources he has available for the tests and for planning them, and what he really wants to know from having run the tests.

LITERATURE SUMMARY--RESISTORS

#L	015	018	033	040	056	084	086
Parameters Accelerated							
Power	no	yes	yes	yes	no	yes	?
Ambient temp Operate or storage	op	op	?		stor		?
Temperature Model							
Arrhenius or time-Temperature Parameter	Arrh	Arrh		tTp	Arrh		Arrh
No. Tested	M	S	L	M	?	M	
Time Consumed	L	M	L	M	?	L	
Some details of results and analysis	no	yes	yes	yes	no	no	no
Extrapolate to operating conditions	yes	yes	yes	yes	yes	yes	yes
Qualitative or Quantitative use	quant	quant	quant	quant	quant	both	both
Matrix		M	?	?			
Constant Stress	C	C	C	C	C	C	C
Step Stress	S	S	S	S			
Failure Time Distribution	log-Normal	Weib	exp., Weib			Weib	
Kind of Resistors	metal film	Ta thin Film	Carbon Film	Metal/Oxide Film	Carbon Comp	Ta thin Film	Film

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Number tested	per run	(or) altogether	Test time	caldendar hr.	(or) total device hr.
Small	1-10	1-100	Short	$<10^2$	$<10^4$
Medium	$10-10^2$	10^2-10^3	Medium	10^2-10^3	10^4-10^6
Large	$>10^2$	$>10^3$	Long	$>10^3$	$>10^6$

? → unknown or not clear

(blank) → not applicable

Weib → Weibull

Exp → exponential

8. Capacitors (dielectrics)

8.0 The description of capacitors is not very complicated (compared to transistors, say). There are very rarely more than three parameters being considered for any one capacitor--usually capacitance, dissipation factor, and insulation resistance (leakage current). Some very extensive, expensive matrix tests have been run on several capacitors, eg, tantalum electrolytic and glass, for predicting the hazard rate vs stress and/or burn-in.

The two components of a severity level for most capacitors are virtually always considered to be applied dc voltage and ambient temperature. In some specialized cases the ac current may also be a component; it can cause severe internal heating.

The model for applied dc voltage (usually abbreviated as just "voltage") is virtually always the "power law", but occasionally is exponential. The power law states that the life of a capacitor is proportional to some power of the voltage, ie, $L \propto V^x$. This statement is somewhat ambiguous since life is not clearly defined. It could be the individual lives, some average life, or it could be related to some parameter of the hazard rate. This situation is analyzed in more detail in Sec. 6.5. The "law" is ambiguous to that extent; so one must be more specific in any particular situation. Most often, the constant hazard rate hypothesis is made, and presumed to hold for all severity levels being considered. This drastically limits (and/or makes equivalent) the possibilities mentioned in Sec. 6.5, viz, the constant hazard rate (λ) is a function of voltage: $\lambda = \lambda_0 (V/V_0)^x$ where λ_0 V_0, x are to be determined from the data. This power law is sometimes extended, using linear cumulative damage, to say that the damage rate is $\lambda = \lambda_0 (V/V_0)^x$.

Occasionally an exponential form is used, viz, $\lambda = \lambda_1 \exp (V/V_2)$ where λ_1 and V_2 are determined from the data. This is especially true when "bruteforce" fitting λ to a linear function of V and T. There are no available comparisons of the two models.

The power law is often used for extrapolation and interpolation of voltages but the particular exponent is known to vary with the voltage, the temperature, the kind of capacitor, and, most probably, the particular batch in which the capacitor was made. Therefore, the grossness of the approximation should be explicitly stated in the analysis. The exponent has a wide range for all capacitors--say from 3 to 12; assuming something like the fifth power law for all capacitors can give extremely misleading answers.

The Arrhenius equation is most often used for the temperature dependence of dielectrics. In this case the hazard rate is constant with time (the Arrhenius rate is constant with time) and is presumed to have the form $\lambda = \lambda_0 \exp\left(\frac{E}{kT_0} - \frac{E}{kT}\right)$ where λ_0, T_0, E are determined from the data. The equation is discussed in more detail in Sec. 4.1 and is compared to the direct exponential form $\lambda = \lambda_1 \exp(T/T_2)$. As mentioned above, this direct exponential form tends to be used in matrix experiments and is used in the "doubling" temperature forms (eg, the rate doubles for a 10°C increase in temperature). Some dielectrics have very steep Arrhenius curves, ie, very high activation energies. Under these circumstances the bulk of damage can be done by a few brief high temperature excursions.

Some manufacturers like to presume that their failure distribution is Weibull with a shape parameter less than 1 which creates a decreasing hazard rate. Most often it is presumed that under accelerated conditions the shape parameter remains the same and the location parameter follows the Arrhenius equation. Very seldom are enough tests run to check out these assumptions very accurately. Usually there are only three points for an Arrhenius curve with a straight line drawn among them. These three points seldom lie anywhere near a straight line and, in the absence of prior information, one would certainly be tempted to draw a very pronounced curvature in the line through the points. In the absence of this prior or extra information no one can say what ought to be done, and this illustrates the difficulties with using accelerated testing for quantitative prediction.

The chart "Literature Summary--Capacitors, Dielectrics" summarizes the literature on accelerated testing of capacitors. As far as can be determined, the test designs and methods were reasonable for the stated or implied purposes. Where poor practice was evident, it was virtually always in the analysis and due to not realizing the limitations of the analytic/statistical procedures being used. Specific reviews should be consulted for detailed comments.

There are no definitive methods for accelerated testing of capacitors and subsequent extrapolation to operating conditions. Each case will depend

LITERATURE SUMMARY--CAPACITORS, DIELECTRICS

#L	001	002	005 022	011	013 070	018	026	027	029
Parameters Accelerated									
DC Voltage	yes	yes	yes	yes	yes	yes	no	?	yes
Ambient Temp. Operate or Storage	op	op	op			op	op?	?	op
Temperature Model									
Arrehenius or Exponential	exp		exp			Arrh	exp	Arrh	exp
Voltage Law (Exponent for power law)	p(2-10)	power	exp	complicated	power				power
No. tested		L	L	M	?	S	S	?	M
Time Consumed		L	L	?	L	M	L	M	S
Some Details of Results & Analysis	no	yes	no	yes	no	yes	no	yes	no
Extrapolate to Operating Conditions	yes	yes	yes		yes	yes	no	no	no
Qualitative or Quantitative Use	quant	quant	quant	quant	quant	quant	qual	qual	qual
Matrix Constant Stress Step Stress	C	C S	C	C	C S	M C S		C	C
Theory Developed	no	yes	no	no	yes	no	no	no	no
Failure time Distribution	exp, Weib.		Weib, $\beta < 1$	Weib.		Weib.	exp.		
Kind of Capacitor	paper	mica	glass	polyethylene cable	mica, Mylar	Ta thin film	electrolytic	Transf. insul	paper, Ta electrolytic

034	035	040	045	050	054	055	057	058	060	068	075	078
yes	yes	yes	yes	yes	yes		no	no	yes	yes	yes	yes
op	op	op	op	op	op	op	amb		op	op	op	op
empirical	exp	Arrh	?	?	exp	Arrh	Arrh	Arrh	exp	Arrh	?	
empirical	p(8)	?	?	?	p(3)				exp	?	?	
L	L	S	?	?	M				L	M	L	L
L	L	S	?	?	M				L	L	L	L
no	no	no	no	no	no	no	no	yes	no	no	no	none
no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	?	
quant	quant	quant	qual	quant	quant	quant	quant	quant	quant	quant	both	
M C	M C	M C S	?	M C	C	C	C	linear cum. damage	M C	M C	M C	M C
no	no	no	no	no	no	no	no		no	no	no	no
empirical	decr. hazard	exp	exp	Weib, $\beta < 1$	exp				exp	?	Weib	
Mylar	mica	glass	vitreous enamel	Solid Ta	ceramic	transf. insul.	wire insul.	transf. insul.	glass	dry Ta	Ta foil	ceramic

---

Number tested	per run	(or) altogether	Test time	calendar hr.	(or) total device hr.
Small	1-10	1-100	Short	$<10^2$	$<10^4$
Medium	$10-10^2$	10^2-10^3	Medium	10^2-10^3	10^4-10^6
Large	$>10^2$	10^3	Long	$>10^3$	$>10^6$

? → unknown or not clear (blank) → not applicable largely on the resources available for the test. Detailed plans are influenced by how much prior knowledge and guesses the engineer is willing to use, what assumptions he is willing to make (the fewer the resources, the more encompassing will be the assumptions), and what information he needs from the tests. Definition of failure, with three performance parameters available, will be an important influence on the outcome of the experiments.

9. Discrete semiconductors

This section covers both diodes and transistors; their methods of acceleration are quite similar. The system state for these is rather complicated since there are usually quite a few parameters that can be important. As with resistors and capacitors, the mechanical and some environmental considerations such as shock, humidity, and salt spray, are taken care of with the stress-strength model of failure and acceptance/qualification testing. There is some disagreement in the literature about whether the life distribution of these devices is logNormal, exponential, or Weibull. It is probably not possible to distinguish between logNormal and Weibull with the accuracy of the data usually available. In times past of course the exponential distribution was most often assumed. Then manufacturers became concerned that their devices might not be getting a fair shake, and showed test results to demonstrate that the devices had a Weibull distribution with shape factor less than 1 (decreasing hazard rate). More recently there have been assertions that devices which are well screened will have an exponential distribution. There is no reason a priori why any particular one of the tractable distributions should fit the data exactly, and any assertions about what must be true are usually definitions of something in the assertion. For example, one might say that a properly screened batch of transistors will have a constant hazard rate. This is a definition of "properly screened".

Temperature acceleration, for most failure modes, is the usual kind of acceleration. The Arrhenius model is the most common one but the exponential is used occasionally. Section 6.5 evaluates the two. Junction temperature is presumed to be the key to failure behavior. Since the junction temperature is not directly measured but is inferred from electrical parameter measurements, there has been some discussion in the literature about the best way of estimating this junction temperature. Differences are observed with power-on vs power-off tests which are associated with surface effects, eg, ion migration. Part of the discrepancy between power-on and power-off tests has been ascribed to poor procedures in estimating the junction temperature and in calculating the dissipated power. The failure mechanism may be a function of voltage or current levels and, if so, it will help if the data are segregated.

It is relatively easy to design matrix tests on a transistor or diode with various voltages, currents, and ambient temperatures. It is much more difficult to run them because it involves very expensive apparatus and a great amount of technical time. Furthermore it is not known how the parameters in the model are affected by process changes, eg, activation energies in the Arrhenius equation.

When matrix tests are run, and a nonlinear equation is to be fitted to the $\ln(\lambda)$, (λ = constant hazard rate), it is not necessary to use P_{input} and T_{ambient} as the parameters to be varied. Since $T_{\text{junction}} = \theta P_{\text{input}} + T_{\text{ambient}}$, it may be wise to rotate the coordinate system; $\theta P_{\text{input}} + T_{\text{ambient}}$ would be one new coordinate and $T_{\text{ambient}} - \theta P_{\text{input}}$ could be the other. This may help to eliminate some of the crossproduct terms (interaction effects).

Accelerated tests are used to evaluate process changes and the presumption is usually made that the comparison at accelerated conditions is the same comparison that would have been made at the standard conditions. This is not known to be true; often there are few if any data to substantiate the assumption. But part of the essence of engineering is making decisions in the face of inadequate data. Running the tests and making the decision is better than not running the tests and making a decision. It is not the purpose of this report to decry this practice, but merely to point out that the engineer using his judgment should know where he is guessing and know where there are reasonable facts to back him up.

With the very long-lived devices now available, accelerated tests are the only way of estimating the life of devices. As mentioned in Sec. 5.2, if the extrapolated values are good enough, regardless of the exact form of the model, then the exact form of the model is not critical and need not be worried about.

The qualitative uses for accelerated testing which were mentioned in Sec. 1 are very important for semiconductors. Some failure modes have been corrected, not because they were expected to cause difficulties under operating conditions but because they got in the way of observing other failure modes on accelerated tests.

The chart "Literature Summary--Discrete Semiconductors" summarizes the literature on accelerated testing of discrete semiconductors. The test designs and methods were reasonable when compared to the resources probably available to run them. Some of the analyses were not explained very well--especially for step-stress tests. As mentioned in Sec. 6, a reasonably convincing background should be available before using a model. Specific reviews give more detail on this point. There were few, if any, matrix tests described in the literature which was surveyed; this is probably indicative of the high costs and difficulties involved.

There are no definitive methods for accelerated testing of discrete semiconductors and subsequent extrapolation to usual conditions. Most often, the testing that can be done will be limited by the resources (time and money, largely). Within those limits, detailed plans will be determined by what models one is willing to assume on the basis of too little evidence. Qualitative step-stress tests, and burn-in tests seem to be the largest application. In this regard, the work in #L-112 involving very accurate measurements of parameter changes under rated or operating conditions should be carefully studied.

LITERATURE SUMMARY--DISCRETE SEMICONDUCTORS (DIODES AND TRANSISTORS)

#L	003	009	012	015	017	030	032	038	039
Parameters Accelerated									
Dissipated Power									
Ambient Temp Operate or Storage	stor	both	both	op	op		stor	both	op
Junction Temp measured		yes			yes		yes		
Temperature Model									
Arrhenius or Exponential	Arrh.	Arrh	Arrh	Arrh	Arrh		Arrh?	Arrh	?
No. tested	?	L	?	M	M			M	L
Time Consumed	M	L	L	M	M			L	M
Some details of Results & Analysis	no	no	no	no	no	no	no	no	no
Extrapolate to Operating Conditions	yes	no	yes	yes	yes	no	no	yes	no
Qualitative or Quantitative use	quant	quant	quant	quant	quant	quant	theory	quant	
Matrix									
Constant Stress		C	C	C	C	?	C	C	C?
Step Stress	S		S	S	S				S?
Failure Time Distribution		exp	exp	log Norm				exp	various
Si or Ge	Ge	both	Si	Si	Ge	Si		?	
Kind of Device	mesa	various	mesa	planar	diff, epit	general	general	various	general

040	052	053	059	062	068	069	071	074	081	083	087	088
		yes	yes	yes					yes	yes	yes	
both	various	both	op	both	?	both	both	various	both	both	op	?
?				yes		yes				yes	yes	yes
?	?	?	exp	Arrh	Arrh	?	Arrh	?	Arrh	Arrh		Arrh
M		?	?		?	L	M	L	M	?	M	?
S		?	?		S	M	M	L	S	L	M	?
no	no	no	no	no	no	no	no	yes	yes	yes	no	no
?	?	yes	yes	yes	yes	no	no	?	no	yes	yes	yes
qual	qual	quant	quant	quant	quant	qual	qual	quant	qual	quant	both	both
C S		C	C	C S	C	C	C	M C S	C S	S	S	S
?					exp	?	?	?				
Si		Si	Ge		Ge	both	Ge	Si	Si	Si	Si	both
various	various	various	hi power	general	alloyed	various	mesa	epit, planar	epit, planar	mesa	planar	various

---

Number tested	per run	(or) altogether	Test time	calendar hr.	(or) total device hr.
Small	1-10	1-100	Short	10^2	10^4
Medium	$10\text{-}10^2$	$10^2\text{-}10^3$	Medium	$10^2\text{-}10^3$	$10^4\text{-}10^6$
Large	$>10^2$	$>10^3$	Long	$>10^3$	$>10^6$

? → unknown or not clear

(blank) → not applicable

10. Integrated circuits

The limitations on accelerated testing of integrated circuits include all of those for discrete semiconductors plus others. An integrated circuit is a much more complex system than a transistor or a diode; it is analogous to a mechanical system where different kinds of things are combined in one unit. Accelerating the testing is difficult because temperature is about the only damager to which all parts of the unit may respond reasonably well, ie, without overloading.

In an integrated circuit a current increase may be shared by only one or two parts of the circuit or may cause one device to overload without affecting the others. Increasing the voltage causes problems because the breakdown voltages of part of the components are reasonably low while others are fairly high. Some of the potential failure modes can be studied by themselves without regard to the other portions of the circuit under accelerated tests--channeling and migration of aluminum conductor material are examples.

Where the fraction of failures is extremely small the production line must be monitored most carefully in order to avoid the introduction of gross irregularities. Accelerated testing is used to check for this without the limitations of uneven responsiveness' being so severe.

On a well established family of devices, the reliability may be so high that step-'stressing' is not applicable. All that it will find is the severity-levels above which the device ceases to be an integrated circuit, ie, the upper limits for the severity levels. Constant-'stress' tests are then run at this limit, and if no failures are generated, something else must be done. Usually this will be trying to go inside the device to make measurements on specific junctions, etc. But with the trends to smaller and smaller device areas, even this will be difficult.

Not many papers are being published on accelerated testing of integrated circuits. The few that have been found and reviewed are sumarized in the chart "Literature Summary--Integrated Circuits". The competitiveness of the market and the lack of spectacular successes to report probably account for the reluctance to publish.

There are no definitive methods for accelerated testing of integrated circuits and subsequent extrapolation to usual conditions. In this respect, integrated circuits are probably the least amenable of the electronic parts to accelerated testing. Individual failure mechanisms can sometimes be accelerated on incomplete or special devices and studied that way.

LITERATURE SUMMARY--INTEGRATED CIRCUITS

#L	019	063	065	066	067	089
Parameters Accelerated						
Dissipated Power				no	yes	yes
Ambient Temp. Operate or Storage	op			?	both	both
Temperature Model Arrehenius or Exponential				Arrh	?	Arrh
No. Tested	?			M	L	M
Time Consumed	?			M	?	L
Some details of Results & Analysis	no	no	no	no	no	yes
Extrapolate to Operating Conditions	no	yes		yes	no	yes
Qualitative or Quantitative use	qual	both	both	qual	qual	quant
Matrix Constant Stress Step Stress	S				?	
Failure Time Distribution						
Kind of Device	general	general	general	general	general	general

---

Number tested	per run (or)	altogether	Test time	calendar hr. (or)	total device hr.
Small	1-10	1-100	Short	10^2	10^4
Medium	$10\text{-}10^2$	$10^2\text{-}10^3$	Medium	$10^2\text{-}10^3$	$10^4\text{-}10^6$
Large	$>10^2$	$>10^3$	Long	$>10^3$	$>10^6$

? → unknown or not clear

(blank) → not applicable

11. Recommendations

Now that the state-of-the-art on accelerated testing of electronic parts has been summarized, where do we go from here? General instructions for planning accelerated tests are given in Sec. 6-10. Useful research can be directed toward the following areas.

1) Use of prior knowledge. While all engineers put their knowledge to use, it is often difficult to put it into quantitative form. Even if that were done, into what equations should it go? The Bayesian approach to probability has some success in this area, but the problems are far from solved. One difficulty is illustrated by the following example. Suppose one wishes to estimate the fraction defective in a population. The most common tractable Bayesian approach is equivalent to assuming a prior number of tests with a certain number of failures, both of which are merely added to the test results. Suppose that there are no failures, either in the prior or in the tests. Then it is fairly easy to show that when the test size is smaller than the prior size, the tests have little influence on the estimate. When the test size is larger than the prior, the prior will have little influence on the estimate. There is only a small region where the test and prior sizes are about the same that both affect the estimate. But this situation is not really what we have in mind when we speak of using prior information. It may be that we have to change our minds, or perhaps, we can modify the methods.

2) Small useage electronic/electromechanical parts. Many parts are used in such small quantities that full scale accelerated tests are not feasible. In what ways can the testing be further compressed/accelerated to obtain as much knowledge as possible about the likely behavior of a part at only a small cost?

3) Integrated circuits. Tests for integrated circuits are difficult to accelerate because of the heterogeneity of the parts in the package, because the upper limits of severity level are too low, because they are often used in small quantities, and because they must have such a long, sure life. With the introduction of Large Scale Integrated circuits, the difficulties are exacerbated and possible avenues for solution are closed off.

4) Cumulative damage models. Only the linear theory of cumulative damage is used for electronic parts. What others might be applicable? What kinds of tests are necessary in order to get ideas for them and to check them out?

5) Damage rate models. About the only models in wide use are the Arrhenius/Eyring model for temperature and the dc-voltage power law for capacitors. The power law for capacitors is known to have severe limitations and the Arrhenius model has difficulties associated with its use. For what components is it worth trying to develop models of damage rate vs severity-level? And how should one go about it?

6) Models for failure. Section 2.2 describes some models for failure, but these are not universally applicable. Integrated circuits are an example of a device with no clearly defined failure models. What makes electronics so different from metallurgy in the relative abundance of failure models? Is behavior that different or is electronics merely undeveloped?

7) Methods of analysis. Extrapolation of accelerated test results requires the use of many models, sometimes in sequence. Few engineers are aware of the statistical methods available for them or how to use them. In some cases, their needs are not directly met by existing formulas and new ones should be developed (Appendix C is an example of such a development). The unmet needs must be identified and then expressed in a form so that the problem implies a solution. Then the solutions must be uncovered and their properties evaluated.

8) K-factors. Factors which reflect the different severity of environments are often applied to the hazard rate (presumed constant with time). What relationships should be developed where hazard rate is a function of time? This problem is raised in Sec. 6.5 (#L-089 also raises and states the problem).

9) Accelerated burn-in. What are the relationships, if any, between accelerated burn-in and accelerated testing? What happens when the state of the device has several dimensions and they are not equally accelerated?

12. Conclusions

Accelerated testing is important and valuable. Despite its limitations it will continue to be used by most everyone because of the higher value received for the lower expenditure of time, money, and material. Engineers work in a world where they must make decisions even though their knowledge is woefully limited. They should neither listen to those who promise that accelerated testing is the solution to all of their problems, nor to those who decry it on the basis of our limited knowledge. A large portion of this report is taken up with the elucidation of the underlying concepts and equations. Here again the engineer must steer a safe course between deceiving himself and others by the connotations of the phrases used, and not worrying about labels but understanding the concepts behind them.

If the engineer does understand the philosophy of accelerated testing and the concepts used to express that philosophy, he knows wherein he is guessing and he knows how much. In this way he need not mislead himself into thinking he has done what he has not. (He can use his own judgment about how much he may mislead others, eg, bosses and project monitors.)

References

1 - Brownlee, Kenneth A., Statistical Theory and Methodology in Science and Engineering, 2nd edition, 1965, Wiley.

2 - Draper, N. and Smith, H., Applied Regression Analysis, 1966, Wiley.

3 - The Encyclopedia of Chemistry edited by George L. Clark, Rhinehold New York, 1957, pp. 817-819.

4 - Handbook of Mathematical Functions edited by Abramowitz and Stegun, AMS 55, National Bureau of Standards, U.S. Government Printing Office, 1967.

APPENDIX A

Names, Definitions, and Illustrations Related to Probability of Success

There is some arbitrariness in these definitions and names since there are no standards. The ones given here seem natural in the context that rate is used in the calculus and they apply to distributions of continuous variables only[1]. Note, in particular, the distinction between hazard rate and failure rate.

Probability of Success $\equiv$ Reliability, R

$$\text{Hazard rate, } h \equiv \frac{-dR/dt}{R} \equiv -\frac{d(\ln R)}{dt} \tag{A1}$$

$$\text{Failure rate, } f \equiv -\frac{dR}{dt}\text{, or } f \equiv -N_o \frac{dR}{dt}{}^{2} \tag{A2}$$

$$\text{Cumulative Hazard, } H \equiv \int_o^t h(\tau)\, d\tau \tag{A3}$$

$$R \equiv e^{-H} \equiv \exp\left(-\int_o^t h(\tau)\, d\tau\right) \tag{A4}$$

$$f \equiv hR \tag{A5}$$

Special case: constant hazard rate.

Let $h = \lambda$, a constant

then $H = \lambda t$ (A6)

$R = e^{-\lambda t}$ (A7)

$f = \lambda e^{-\lambda t} = \lambda R$ (A8)

Special case: very high reliability

$R \approx 1$

$h \approx f$

---

[1] If the variables are not continuous either explicitly or conceptually, difficulties arise in trying to define these parameters.

[2] N_o is the initial number of elements. This expression is rarely used in theoretical developments, but is sometimes convenient in reporting data.

From Eq. A4, the reliability is directly related to the area under the hazard rate curve. In Fig. A-1, the area between t_1 and t_1^* is obviously the same as that between t_2 and t_2^*. In Fig. A-2, the area between t_1 and t_1^* is just as obviously more than that between t_2 and t_2^*. Therefore, with a decreasing hazard rate, the probability of failure (for a given mission) decreases as time goes by--the "weaker" ones fail, leaving only the "stronger" ones.

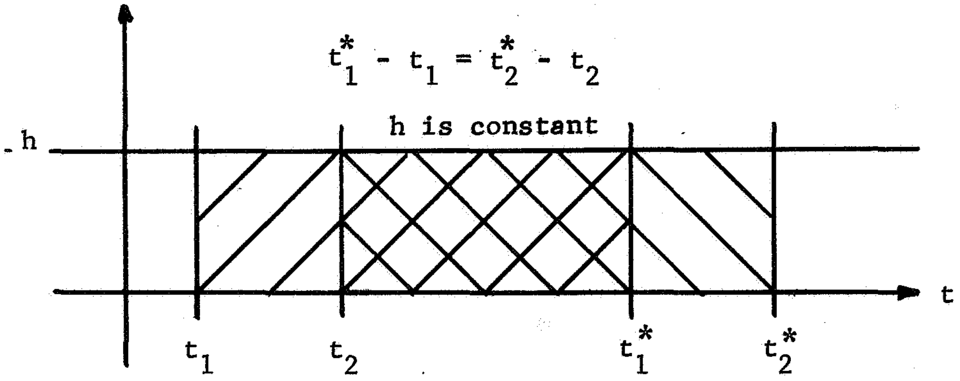


Fig. A-1. Constant hazard rate.

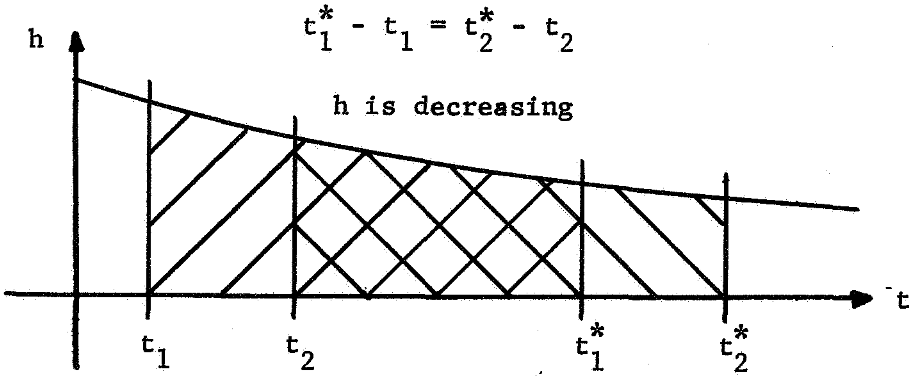


Fig. A-2. Decreasing hazard rate.

APPENDIX B

Estimation of Hazard Rate Using the Slope of a Survival Curve

Very often one wishes to estimate the hazard rate from data under conditions where the hazard rate may not be constant. Then the following relationships are of interest:[1]

1) If $-\log_e R$ is plotted vs time this is equivalent to plotting the cumulative hazard, $H(t)$ vs time. The slope (m) of that line will be the hazard rate, ie, $h=m$. If the line is straight, the slope is constant as expected for the exponential curve.

2) In some cases because of the large span of time, it is inconvenient to plot time linearly. Suppose that $-\log_e R = H$ is plotted vs $\log_e$ time. Then it is easy to show that the slope (m) of the line is $h \times t$, or $h = m/t$.

3) If Weibull paper is used this is equivalent to plotting $\log_e \log_e 1/R = \log H$ vs log time, and the slope (m) of this line is $m = t \times h/H$, or $h = m \frac{H}{t}$. It is interesting to note that H/t is the mean hazard rate, $\bar{h}$, to that point in time. Thus $h = m\,\bar{h}$.

4) For completeness (rather than utility), the case for a graph of R vs t is included. The slope, m, of the curve is $-R \times h$, or $h = -m/R$.

In general it is best to use graph-scales for which the curve has the most nearly constant slope. The slope at any point is then much easier to calculate and the resulting value of h will be more accurate, due to the absence of graphical and roundoff errors. The results are summarized in the table below

Calculation of hazard rate from a slope (m)

rough description	Plotting axes Vertical	 Horizontal	hazard rate
linear	R	t	$-m/R$
semilog	$H = -\ln(R)$	t	m
log-log	H	$\ln(t)$	m/t
Weibull	$\ln(H)$	$\ln(t)$	$m(H/t) = \frac{m}{t} \times \ln(1/R)$

---

[1] These are most easily visualized in terms of a graph, and are thus explained that way. They apply equally well of course to any numerical calculations of slope. The notation is explained in Appendix A.

APPENDIX C

Analysis of Tests when Hazard Rate Is Constant in Time and Obeys the Arrhenius Equation[1]

Assumptions:

1a. The hazard rate of the process is given by the Arrhenius equation[2]

$$\lambda(T) \equiv A\, e^{-E/kT} \equiv \lambda_{ref}\, e^{-E\left(\frac{1}{kT} - \frac{1}{kT_{ref}}\right)} \equiv \lambda_o\, e^{-E\left(\frac{1}{kT} - \frac{1}{kT_o}\right)} \qquad \text{(C-1)}$$

where

λ is a hazard rate and is a function of temperature.

A is a constant

E is an energy, often referred to as the Activation Energy

k is Boltzmann's constant ($0.86171 \times 10^{-4} \frac{eV}{°K}$, $\frac{1}{k} = 1.16049 \times 10^{4} \frac{°K}{eV}$)

T is an absolute temperature

ref is a subscript denoting a reference condition

o is a subscript denoting a special condition (to be defined below).

1b. Since all of the parameters above are independent of time, the constant hazard rate formulas are applicable.

2. Each experiment is run at a constant temperature and the failure behavior is recorded. For each experiment, time and number of failures are the data (either, or both, can be the random variable).

3. The results of the experiments are statistically independent.

---

[1] A more complete derivation and analysis has been submitted to the Journal of the Electronics Division, Amer. Soc. Quality Control for publication.

[2] The sign $\equiv$ is used to imply an identity and/or a definition.

It is convenient to introduce[2]

$$x_i \equiv -\left(\frac{1}{kT_i} - \frac{1}{kT_0}\right) , \; h_0 = \ln\lambda_0 \quad h = \ln\lambda ,$$

where T_i is the i^{th} test temperature;

then

$$\lambda_i \equiv \lambda_0 \, e^{E x_i} \equiv e^{h_0 + E x_i}$$

Then the method of Maximum Likelihood yields the following best values for E and h_0:

$$\sum_i n_i x_i = 0 ,^3 \tag{C-2}$$

$$\sum_i t_i x_i e^{\hat{E} x_i} = 0 , \tag{C-3}$$

$$h_0 = \ln \frac{\sum_i n_i}{\sum_i t_i e^{\hat{E} x_i}} , \tag{C-4}$$

where n_i = total failures at T_i,

t_i = total device time at T_i.

---

[2] Unfortunately this notation is not easy to remember; but it is easy to write, and makes the equations much simpler to read. h can remind one of <u>h</u>azard rate; and x can remind one of the <u>x</u> axis, which is where $\frac{1}{kT} - \frac{1}{kT_0}$ is usually plotted. x has the dimensions of reciprocal energy.

[3] This equation defines the origin for x. Under these circumstances the estimates, $\hat{E}$ and $\hat{h}_0$, are linearly uncorrelated--at least in an asymptotic sense.

Equation C-2 is easily satisfied by the proper choice of $\frac{1}{kT_0}$ (after the data are taken of course), but satisfying Eq. C-3 places some restrictions on the n_i:

(a) If $n_i \neq 0$ for at least 2 different i, there is no difficulty;

(b) If $n_i \equiv 0$, there is no solution (except the trivial one of

$$\hat{\lambda}_0 = e^{\hat{h}_0} = 0, \text{ and } \hat{E} \text{ undefined});$$

(c) If $n_i = 0$ for $i = j$ only, T_j cannot be the highest or lowest Temperature. If it were to be one of those, Eq. 12 could not be satisfied except by $E \to \pm \infty$.

Equation C-3 is readily solved for $\hat{E}$ by Newton's method of iteration; then Equation C-4 is easily evaluated. More calculus and algebra give the following estimated variances (still according to the Method of Maximum Likehood):

$$\text{est.var}\,(\hat{h}_0) = \frac{1}{\sum_i n_i}, \tag{C-5}$$

$$\text{est.var}\,(\hat{E}) = \frac{1}{e^{\hat{h}_0} \sum_i x_i^2 \, t_i \, e^{\hat{E} x_i}} = \frac{1}{\sum_i x_i^2 \, \hat{m}_i} \tag{C-6}$$

where $\hat{m}_i = \hat{\lambda}_i \, t_i$ = estimate of expected number of failures at T_i. The estimates $\hat{h}_0$ and $\hat{E}$ are statistically independent[3] so we have for any $\hat{\lambda} \equiv e^{\hat{h}}$, $(\hat{h} = \hat{h}_0 + x\hat{E})$:

$$\text{est.var}(\hat{h}) = \text{est.var}(\hat{h}_0) + x^2 \; \text{est.var}(\hat{E}) \; . \tag{C-7}$$

For most T (and consequently, x) of interest x^2 est.var$(\hat{E}) \gg$ est.var$(\hat{h}_0)$ so that (est.sd is the estimated standard deviation)

$$\text{est.sd}(\hat{h}) \simeq x \; \text{est.sd}(\hat{E}). \tag{C-8}$$

It is the factor x that causes est.sd$(\hat{h})$ to be so large when accelerated tests are extrapolated back to operating temperatures.

Since the equations for $\hat{E}$ and $\hat{h}_0$ cannot be explicitly solved, it is virtually impossible to find their probability distributions. However, the following equations are reasonably accurate, even for a minimum number of failures.

$$\eta_E = \frac{\hat{E} - E_{tru}}{est.sd(\hat{E})} , \qquad \eta_h = \frac{\hat{h} - h_{tru}}{est.sd(\hat{h})}^{4} , \qquad \text{(C-9)}$$

where η has a standard Normal[5] distribution. To a rough approximation, this is borne out by simulation tests that have been run. The exact distributions depend on the details of the tests.

It is possible to set confidence limits on $\hat{E}, \hat{h}$, by using Equation C-9. Confidence limits on $\hat{\lambda}$ are calculated from those on $\hat{h}$; the $\hat{h}$ interval must be calculated first, then transformed to a $\hat{\lambda}$ interval.

---

[4] The subscript "tru" stands for the true value.

[5] A standard Normal distribution has mean = 0, variance = 1.

APPENDIX D

Step or Progressive 'Stressing' Using the Arrhenius Equation and Linear Cumulative Damage

Let damage be proportional to

$$D = \int_{o}^{t} R \, d\tau$$

where D = damage

R = damage rate = $e^{A - E/kT}$ (Arrhenius equation)

t,τ = time

T = Absolute temperature

k = Boltzmann's constant

E = so-called activation energy

1a. Let $T = a + b\tau$

where

a,b = constants

then

$$D_1 = \int_{o}^{t} e^{A - \frac{E/k}{a+b\tau}} \, d\tau.$$

This is expressible in terms of the Exponential Integral. See Ref. 4, p. 228, Sec. 5.

1b. $T = a + bi$

where b = increment in temperature

i = index

then $D_2 = \sum_{1}^{n}{}_{i} \, e^{A - \frac{E}{a+bi}} \, t_{step}$. This is not a tractable sum.

2. Let $\frac{1}{T} = a + bt$ or $a + bi$

$$\text{then } D_1 = \int_{o}^{t} e^{A - \frac{E}{k}(a+b\tau)} \, d\tau = \frac{k}{Eb} \{ e^{A - \frac{Ea}{k}} - e^{A - \frac{E}{k}(a+bt)} \}$$

$$\text{or } D_2 = \sum_{o}^{n-1}{}_{i} \, e^{A - \frac{E}{k}(a+bi)} \, t_{step} = t_{step} \, e^{A - \frac{Ea}{k}} \, \frac{1 - e^{b\,n}}{1 - e^{b}}$$

3. Let $e^{-\frac{E}{kT}} = a + bt$ or $a + bi$

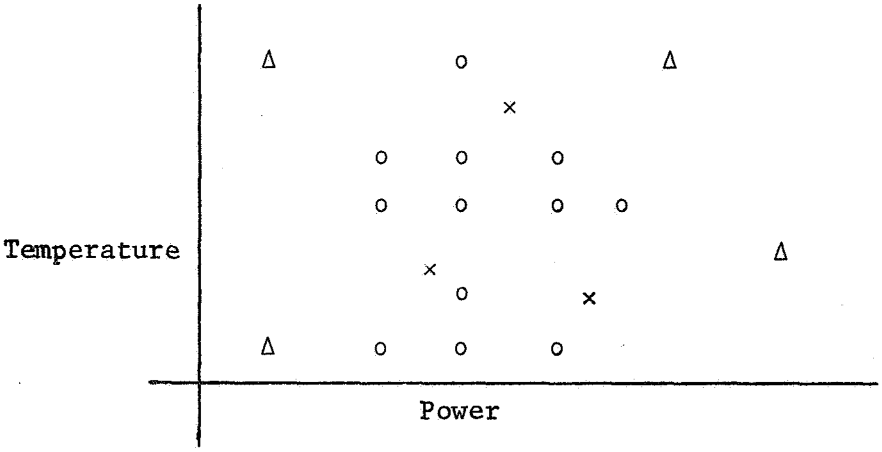
then $D_1 = \int_0^t (a + b\tau)d\tau = t(a + \frac{1}{2} bt)$

$$D_2 = \sum_{i\,0}^{n-1} (a + bi)\ t_{step} = nt_{step}\left(a + \frac{1}{2} b(n-1)\right)$$

APPENDIX E

Interpolation vs Extrapolation

Interpolation means that the new point (set of values of the 'stress' parameters) at which evaluation is desired lies very near to or within the "data" points (values of the 'stress' parameters at which data were taken). Extrapolation means that the new point lies well outside of the "data" points. For example, suppose failure data were taken according to the points on the following chart as shown by the circles (o).



Then the parameters of a model for failure rate were adjusted to give a good fit to the data. If the model is evaluated at the ×'s for example, that is interpolation. If it were to be evaluated at the Δ's, that would be extrapolation.

In the one dimensional case (only one 'stress' parameter) the definitions are simpler: If the new point is within the extremes of the original ones, it is interpolation, if it is outside them, it is extrapolation.

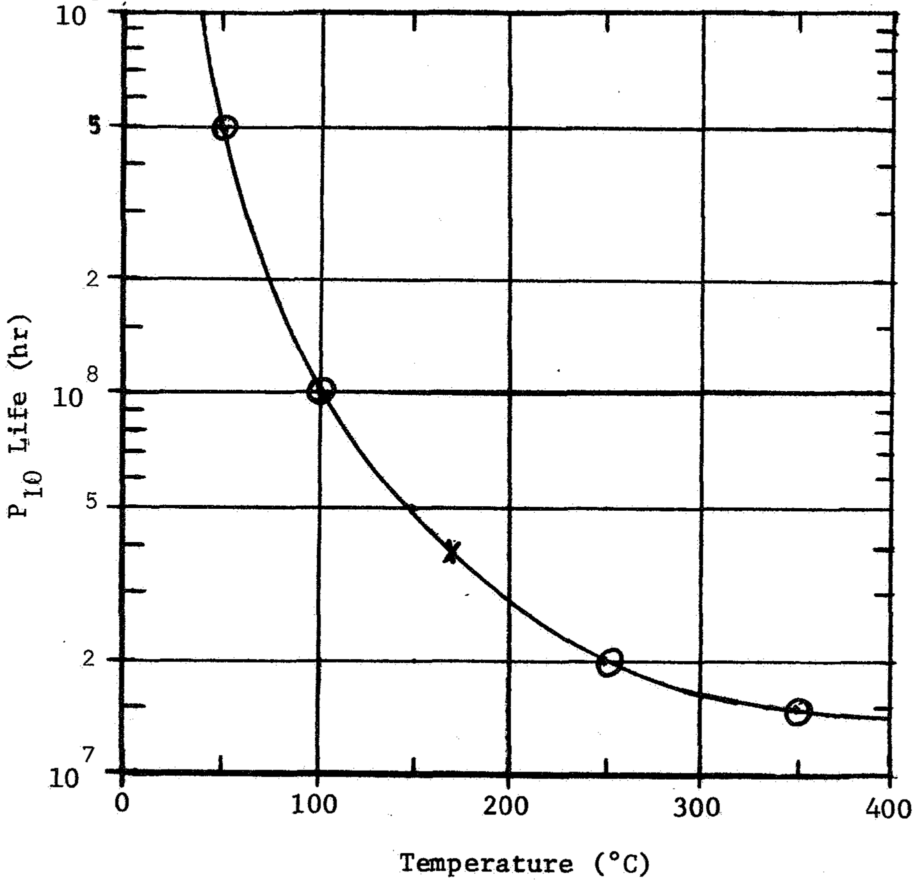
APPENDIX F

Life of a Transistor when the Temperature Fluctuates

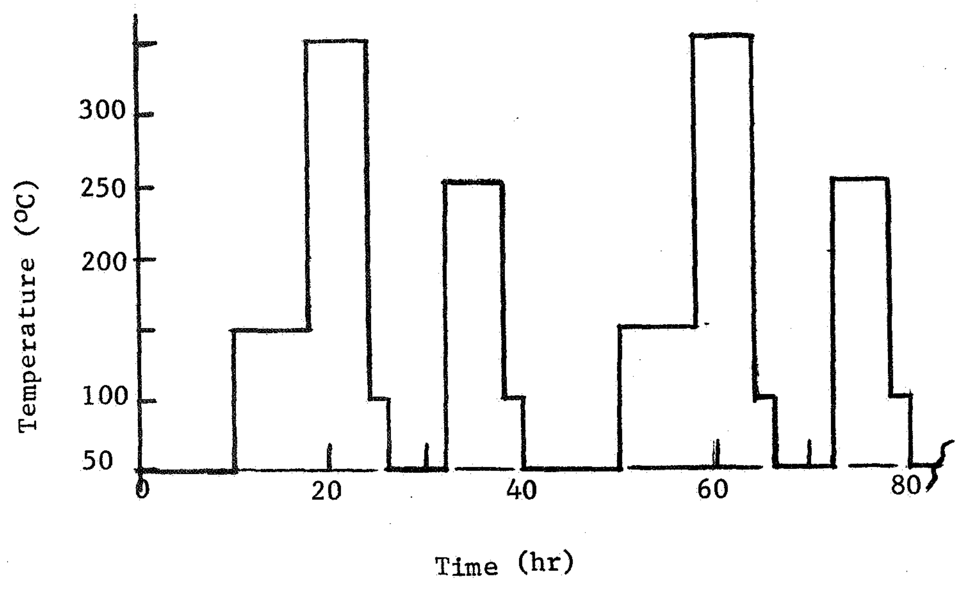
Assumptions:

1. The curve of life (appropriate percentile) vs temperature (at constant temperature) is known.
2. The severity level can be completely characterized by a temperature.
3. Linear cumulative damage is appropriate.
4. No new failure modes, which would decrease the life, are introduced by the temperature changes. (In the theoretical development, this is irrelevant since #3 determines the method of calculation. But when wondering whether or not #3 applies, this is something to consider.)

Let the P_{10} life (10% will fail before that time) be given by the life curve below and the temperature profile be a regularly repeating pattern as shown in the following curve.



Operating Profile



The following chart can be developed from the P_{10} life curve and the temperature profile.

	Temp.	P_{10} life	Fraction of life		Damage rate	Fraction of damage	
	(^oC)	(10^8 hr)	(hr/period)	(%)	(10^{-8}/hr)	(10^{-8} L/hr)	(%)
actual	50	5.0	10+6	40	.20	.08	3.4
	100	1.0	4	10	1.0	.10	4.3
	150	0.50	8	20	2.0	.40	17.2
	250	0.20	6	15	5.0	.75	32.2
	350	0.15	6	15	6.7	1.00	42.9
equivalent	162	L=0.429	40	100	2.33	2.33	100

The damage rate is the reciprocal of P_{10} life. The fraction of damage has units of 10^{-8} L/hr where L is the presumed equivalent P_{10} life. This fraction is calculated by multiplying the numbers in the 2 preceding columns. It is from the total of fraction-of-damage column that L is calculated, viz, the total must be unity. From the P_{10} life curve, it can be shown (for what it's worth) that a constant temperature of 162°C would give the same P_{10} life.

It is interesting to compare the % life column with the % damage column, eg, at 350°C, 15% of the life causes 43% of the damage; while at 50°C, 40% of the life causes less than 4% of the damage.

From Sec. 3.6 it should be remembered that $L = 42.9 \times 10^6$ hr will not be the actual P_{10} life, but is presumed to be close to it.

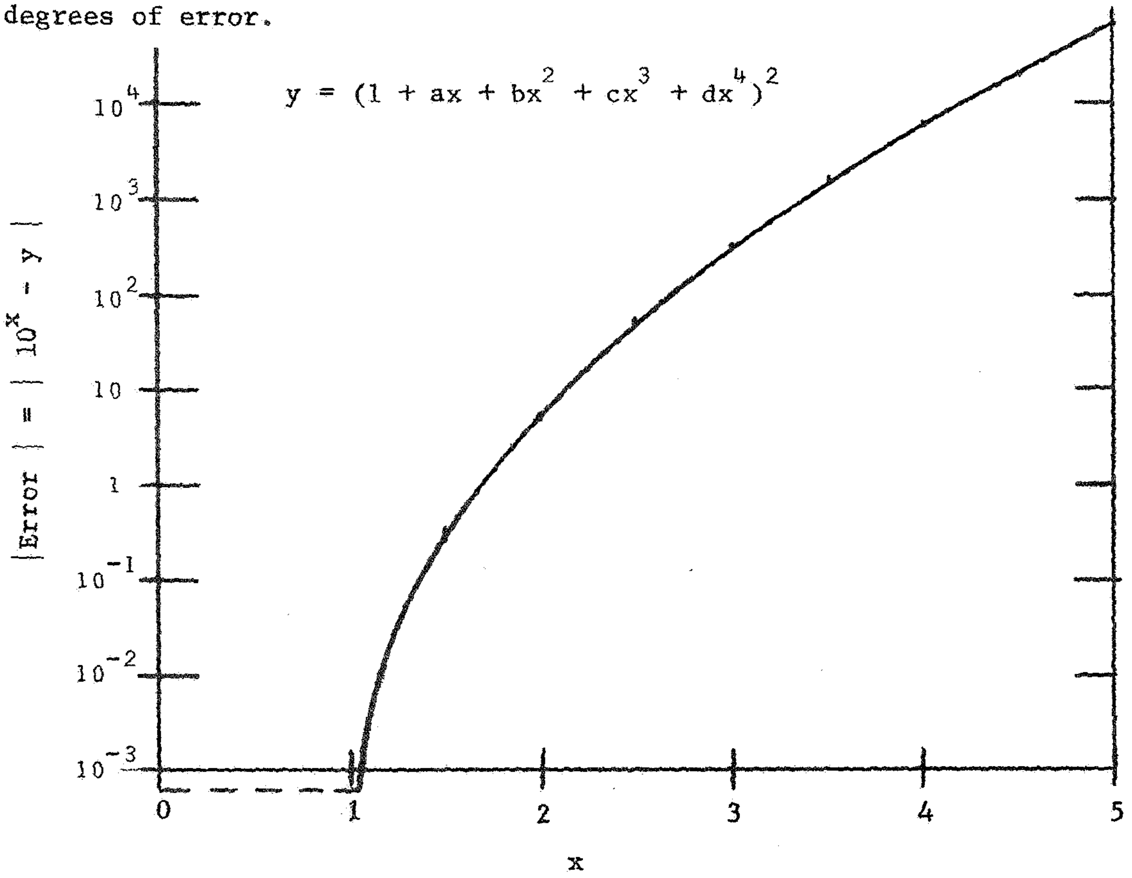
APPENDIX G

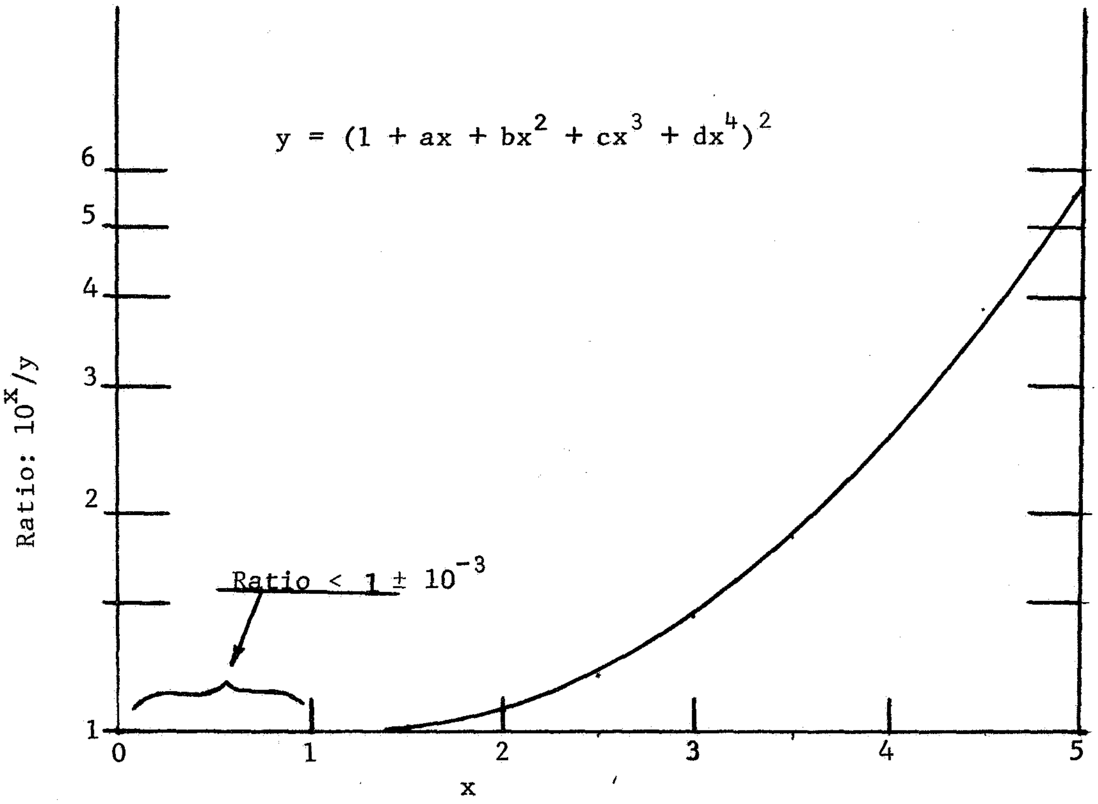
Dangers in Extrapolating a Truncated Series

The main text outlaws extrapolation when a truncated series is fitted to a set of points (assuming that the rare case of exact model is not present). The reason is that the higher order terms get out of hand rapidly when the region over which the good fit was calculated is exceeded.

As an example, a truncated series which will calculate 10^x to ± 0.001 or better, is used. The calculation is accurate only for $0 \leq x \leq 1$. The two graphs below show what happens over the range $0 < x < 5$. One graph shows the ratio of true to calculated value, and the other shows the absolute error. The dotted line means that the error is less than 10^{-3} (it was not calculated more accurately than that).

If more terms were added to give a better fit within the 0 to 1 interval, the behavior outside would be even worse. This example merely illustrates the dangers in this kind of extrapolation, other examples would show different degrees of error.





$y = (1 + ax + bx^2 + cx^3 + dx^4)^2$
Ratio: $10^x/y$
6
5
4
3
2
1
Ratio < 1 ± 10^{-3}
0
1
2
3
4
5
x

APPENDIX H

Maximum Likelihood, Least-Squares, and Estimating the Parameters of a Straight Line

Assume:

1) The process can be described by the general equation:

$$y = f(x) + \sigma(x)z$$

$$\bar{y} = f(x)$$

where z has a standard Normal distribution:[1]

2) The values of $y = y_i$ (assuming that f and σ are known functions and that x_i is given) are statistically independent.

Then it can be shown by the method of Maximum Likelihood that one should minimize the expression

$$\ell = \sum \ln\sigma_i + \tfrac{1}{2} \sum \left(\frac{y_i - f_i}{\sigma_i}\right)^2 . \quad ^2$$

When the σ_i are known, to minimize ℓ is to minimize the sum of the squares of the deviations, $y_i - f_i$; hence the name "least squares". All the appropriate formulas can be derived by minimizing ℓ, regardless of whether the parameters of the function $\sigma(x)$ are known or not. The form of both f(x) and $\sigma(x)$ must be known of course.

For this example, let $\sigma(x) = \sigma =$ constant and let $f(x) = mx + b$. The problem is to determine σ, m, b so that

$$\ell = N \ln\sigma + \frac{1}{2\sigma^2} \sum [y_i - (mx_i + b)]^2$$

is minimized. This is done by the usual methods of calculus. It is also desireable that the estimates of σ, m, b be statistically independent. This is assured (asymptotically) if the following equations are satisfied:

---

[1] Standard Normal: mean = 0, variance = 1

[2] As is customary: $\sum$ means to sum i over all N points, $f_i \equiv f(x_i)$, $\sigma_i \equiv \sigma(x_i)$. It is easy to see, here, that the weight for each point is $1/\sigma_i^2$, as mentioned in the main text.

$$\left.\frac{\partial^2 \ell}{\partial m \partial b}\right|_{\wedge} = 0, \quad \left.\frac{\partial^2 \ell}{\partial m \partial \sigma}\right|_{\wedge} = 0, \qquad \left.\frac{\partial^2 \ell}{\partial b \partial \sigma}\right|_{\wedge} = 0.$$ [3]

The second two are automatically satisfied. The first is satisfied by choosing the origin for x such that $\sum x_i = 0$. In the following equations, it is presumed this has been done.

$$\hat{b} = \frac{\sum y_i}{N},$$

$$\hat{m} = \frac{\sum x_i y_i}{\sum x_i^2},$$ [5]

$$\hat{\sigma}^2 = \frac{\sum (y_i - \hat{f}_i)^2}{N}.$$ [5]

But the really important estimates are the variances of $\hat{b}$, $\hat{m}$, $\hat{\sigma}$, and $\hat{\bar{y}}$. These are calculated from the general relationship

$$\text{est.var}\ (\theta) = \left(\left.\frac{\partial^2 \ell}{\partial \theta^2}\right|_{\wedge}\right)^{-1}.$$ [4]

---

[3] The hat symbol (^) is used to denote the least-square estimate. The symbol $\ldots|^{\wedge}$ means to evaluate the expression at the ^ conditions.

[4] The notation est.var (θ) means estimated variance of $\hat{\theta}$, where θ is any parameter being estimated. All the cross-partials must be zero.

[5] Remember that the origin of x has been adjusted so that $\sum x_i = 0$.

It is easy to derive the following equations:

$$\text{est.var } (\hat{m}) = \frac{\hat{\sigma}^2}{\sum x_i^2},$$ [5]

$$\text{est.var } (\hat{b}) = \frac{\hat{\sigma}^2}{N},$$

$$\text{est.var } (\hat{\sigma}) = \frac{\hat{\sigma}^2}{2N},$$

$$\text{est.var } (\hat{\bar{y}}) = x^2 \text{ est.var } (\hat{m}) + \text{est.var } (\hat{b}).$$ [5]

The equation for est.var $(\hat{\bar{y}})$ would not be this simple if the estimates of m and b were not statistically independent; since they are, the formula is derived from the fact that the variance of a sum is the sum of variances (given statistical independence). Since the first term in the equation for est.var $(\hat{\bar{y}})$ is usually much greater than the second, for any extrapolation, the estimated standard deviation (est.sd) can be written as

$$\text{est.sd } (\hat{\bar{y}}) \approx x \text{ est.sd } (m) = x \frac{\hat{\sigma}}{(\Sigma x_i^2)^{\frac{1}{2}}}$$

It is from this equation that the picture in Sec 5.1 was drawn.

It is of interest to some people that maximum likelihood estimates may be biased. In the above estimates, it is readily noted that $\hat{\sigma}^2$ is biased. This is neither good nor bad in itself, but often the bias is eliminated by the usual formulas. Remember, however, if θ^* is an unbiased estimate of θ, g (θ^*) will not, in general,[6] be an unbiased estimate of $g(\theta)$.

---

[6] If θ^* is an unbiased estimate of θ, $g(\theta^*)$ is an unbiased estimate of $g(\theta)$, if and only if, g (θ) is linear in θ.

Therefore if $\hat{\sigma}^2$ is corrected to be unbiased, $\hat{\sigma}$ will not be unbiased. A big reason that s^2 (the unbiased estimate of σ^2) is used so often is that s is required in many statistical formulas.

Engineers, when faced with an "unbiasing" decision for $\hat{\theta}$ should compare the difference it will make with the est.sd $(\hat{\theta})$, since est.sd $(\hat{\theta})$ is a measure of the uncertainty in $\hat{\theta}$. Generally, the difference will not have any engineering significance. If, on the other hand, the engineering significance should be great, (eg, biasing or unbiasing will cause an important decision to be reversed) then be very careful in deciding what function of the parameter should have an unbiased estimate. The hazard rate is a good example of the difficulties that can arise; assume the hazard rate is constant and estimated by $\hat{\lambda}$. Then which do you want unbiased, $\hat{\lambda}$, $\hat{M} = 1/\hat{\lambda}$ or $\hat{R} = \exp(-\hat{\lambda}t)$? All will have different values of λ^*, the value which gives an unbiased estimate of the parameter of concern!

LITERATURE LIST

The references that have been abstracted and reviewed during this study are listed in serial number sequence (#L-). Beneath each serial number is a rating from 0 to 4 which denotes the pertinence to accelerated testing of resistors, dielectrics, discrete semiconductors or integrated circuits: 0 is not pertinent (but the title sounded good) and 4 is most pertinent.

This list is not a bibliography for the report, but some of the ideas mentioned in the text were obtained while reviewing the references. The quality of these references varies from excellent to terrible, but a quality rating is not given here.

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